INFORMATION PROCESSING CAPACITY IN SINGLE AND DUAL SENSORY CHANNELS

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ABSTRACT

The rate at which man can assimilate and make discriminating responses to a continuous stream of information from the environment has become a question of importance for the integration of man in modern high gain man-machine systems. Previous studies have shown that if information occurs at a rate of more than 1 event per half second, man's ability to respond suffers a time decrement. The time decrement has been identified as being caused by the Psychological Refractory Period. Another explanation of this phenomenon has been made under the title of the Expectancy Hypothesis. The Expectancy Hypothesis postulates that the decrement mentioned above is due to a lack of expectancy on the operator's part for events occurring in relatively short time intervals.

This paper postulates that both these positions have merit and attempts to include them both under a third more generalized formulation which is identified as the Information Hypothesis. The position is taken that the upper limit of response capability only is determined by refractory characteristics. Information processing is

posited to be a continuum whose scale points are determined by expectancy which can be quantified in probability terms and which can be incorporated into a theoretical formulation based on Information Theory.

The Psychological Refractory Period Hypothesis leads to the conclusion that humans are single channel information processing systems while the Expectancy Hypothesis suggests that given the appropriate expectancies, humans can be multichannel systems.

The study described herein attempts to show how the human organism can appear to be a multichannel system while in reality he is indeed single channel. Further, the study attempts to determine if the Shannon-Wiener formulation of the definition of information is adequate for the context of human information processing.

In order to accomplish its purposes, the study required the simultaneous presentation of continuous streams of information through two transducer systems in the organism. This technique was used both within and between sense modalities. The modalities investigated were the visual sense and the auditory sense.

Evidence was accumulated which indicated that indeed the rate of information processing was dependent on the amount of information transmitted. Further, the results of the study indicated that information values based on the Shannon-Wiener formulation which is in turn based on relative frequency measures of events were not adequate if events were entirely experimenter defined. The concept was developed that experimenter defined unitary events may themselves contain informational components which must be evaluated in informational terms. Thus for an adequate definition of an event, the probability of the event occurrence must be weighted by the probabilities of the attributes or components of the event. It was postulated and the results of the study were interpreted as indicating that information is carried in three domains, the stimulus domain, the response domain and the domain of time. Thus for any specific event the information contained in the event is a function not only of the event itself but also of the information contained in the domains indicated. It was further suggested that the sense modality receiving the information has characteristics which differentiate its capacity to process the information from the capacity of other sense modalities. Hence, a weighting factor must be applied to the information equation to relate it to the sense modality involved.

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CHAPTER I

INTRODUCTION

In the relatively brief period of time since the end of World War II, significant increases have developed in man's capacity to create complex systems of tools. These tools have permitted man to extend the environment in which he can exist to spheres which had been hitherto inaccessible to him. Previously, man's tools consisted primarily of extensions of his own effector system. Thus, man's function in the system was always that of decision and the initiation and control of all aspects of tool operation. The more recent complex tool systems have the capability of performing tasks which formerly had been the exclusive property of man. Some of these tasks include lower-level decision functions, such as error-nulling in a tracking task, routine navigational computations and appropriate and directional corrections. It has been stated that man's position in the present day complex man-machine system is coming to be that of a back-up system which goes into overt action in the event of a malfunction of the automated elements of the machine system. In addition, man may also serve as a reserve high level decision maker when a state of affairs occurs in the system environment which had not been preprogrammed into the system and for which the system has no suitable response. Man's presence in the system permits him to evaluate the character of such an environmental change and to initiate the appropriate response into the machine system. This flexibility increases the probability of success for a mission which otherwise would meet with failure.

For man to operate successfully in the role depicted above, he must have available to him information from the environment which will guide him in making decisions. As a result of rapid developmental advances in the area of high speed machine systems, the amount of information which man can process per unit time becomes of paramount importance.

Man is dependent on his sensory system for the receipt of environmental information. The integration of the incoming information with knowledge existing in man's system and the decision process which ensues is generally conceded to occur cerebrally. Thus, man's information processing capacity per unit time is dependent on the rate at which his sensory system can sample the environment, the rate at which the samples can be transmitted to the appropriate cerebral locations, and the rate of integration. Once these processes have been accomplished, the final limitation is imposed by the rate at which man can respond. Viewing the problem externally, man's information processing capacity can be limited by either the rate of sequential information inputs, or the number of simultaneous parallel inputs, or both.

This study will concern itself primarily with the parallel input question.

CHAPTER II

HISTORY AND THEORY

Any time an organism behaves as the result of some event occurring in the environment, information has been processed. Any psychomotor response made to an environmental stimulus is an indicant of information processing and rate or capacity for information processing can be inferred from the speed of response. In the context of this study, isolated instances of information processing are of less interest than situations which involve a continuous stream of information. Studies most relevant to this situation involve sequential responding to sequential randomly occurring stimuli. One of the earlier studies examining this paradigm was identified as a study of the Psychological Refractory Period. This chapter will review the work and conclusions evolved from the Psychological Refractory Period hypothesis, as well as those derived from the Expectancy hypothesis. In addition, an alternative conceptual approach will be presented under the title of the Information Hypothesis. While the rubric, information processing, is a term of broadly generalized application, in the present context it will be used to define a condition where a stream of independent inputs obtains.

The Psychological Refractory Period

<u>The Telford hypothesis</u>. Seventeen years after Telford (1931) identified the Psychological Refractory Period (PRP), demands of World War II generated development of complex man-machine systems which required more research and knowledge concerning the phenomenon. Telford had found that the second of two sequential reaction time measures was increased when the interstimulus interval between two successive stimuli was reduced to less than .5-sec., Craik (1947), Vince (1948), and others (Davis, 1956, 1957, 1959: Fraisse, 1957: Welford, 1959) conducted studies which supported Telford's findings. Telford had given the name PRP to this phenomenon because he felt that it must be related to the refractory period of nerve function which had been previously identified by the physiologists. The enormous discrepancy between the times involved in neuron refraction and PRP would have to be resolved before the precise nature of the function could be defined. In many of the studies cited above, the fact that the same effector response mechanism was used to respond to both the initial and second stimulus was not considered a contributing factor to the asymmetrical intermittancy of the responses. In other words, the slowness of the .5-sec. was not considered to be due to any mechanical-physiological relationship of nerve transmission and muscle limb performance. Craik cites

as evidence the fact that a finger can be moved voluntarily as fast as eight times per second.

Modifications of the PRP hypothesis. The investigators cited above also discovered a phenomenon which did not conform to the situation just described. It was observed that when two sequential stimuli were separated by a very short time interval (less than 50-msec.) there was no increase in the reaction time of the second response. The subject responded to both stimuli in a single continuous motion. The investigators inferred that the subject had grouped both stimuli into a single stimulus complex and responded with a unitary complex response. This particular phenomenon was felt to be distinct from responses which occurred to stimuli separated by intervals greater than 50-msec. and less than .5-sec. The term 'grouping' was used to distinguish this particular class of response.

Manual responses. Evidence concerning the nature of quick manual responses stems from studies by Taylor and Birmingham (1948). By taking the first, second, and third derivatives of the extent of the movements made over a time sample in a tracking task, it was found that high-speed control movements were not ballistic, as had been previously assumed. It was found that the movements were composed of asymmetrical accelerating and decelerating sequences. The time relationships holding between the asymmetries indicated that they occurred at such speeds that it would be impossible for the state of one element of movement to trigger or be the stimulus for the next stage of movement. Rates of neural transmission were far too slow to provide the necessary cybernetic function in the time period indicated.

Taylor and Birmingham postulated the existence of a mechanism such as camming or pre-programming to account for high-speed finite responses. As they viewed it, a sequence of quick movements had to be learned as a slow movement sequence and when sufficiently well learned, it was possible for the operator to reel off the sequence as a program. Once initiated, the program could not be stopped until it had reached completion. Thus a single informational input, the trigger for the program, initiated a response which contained more information than the stimulus. The added information came from the pre-programmed element of the response which was already existing in the organism.

In the studies which examined the existance of PRP, it was precisely this type of cammed function which the experimenters sought to avoid. The object of PRP studies was to determine the rate at which unpredictable stimuli could be responded to when presented serially. Each serial stimulus in PRP studies requires the operator to make a decision and one response only. Pre-learned programming of several responses cannot occur. The conclusion inevitably follows that the delay observed in PRP must, in part at least, be due to the decision process. It has been conclusively demonstrated that the response effector system is capable of much faster responses.

Welford's hypothesis and 'organization'. Welford (1952) elaborated the concept of PRP into a theory with wide implications. He posits that PRP is entirely a central process and states, "--no two central organizing times can overlap." A deduction from this hypothesis is that man is a single channel data processing system. Welford is in accordance with others in supporting the position that the refractoriness found in PRP is due to a central function associated with decision or organization. This position leads to a crucial question. Is the organism refractory for the entire organizing period, totally and completely?

One can hypothesize that several organizing functions must occur cerebrally before a neural command can be initiated to the muscle structure of the effector system. These are listed below.

1. Information from the environment must enter the system through the sensory pathways.
2. On the basis of instructions, training or previous experience, the organism must have a response effector system which is prepared to respond to the environmental information with a specific response class selected from a population of possible response classes.

3. Information from the environment must be integrated with information existing within the organism, which permits identification of the environmental stimulus as a member of a particular class of information and the specific identity of the member within the class.
4. A decision must be made as to which class of response in item 2 is appropriate to item 4.
5. A decision must be made as to which specific member of the response class is appropriate for the specific informational input.
6. A command must be initiated over the appropriate neural network which will result in the appropriate effector response.

The necessity for expectancy. It is apparent from the hypothesized organizing functions listed above that the entire information processing function contains many possible decisions. Merely assigning delay observed in PRP to the central decision function explains little. One would like to know which of the decisions contributes to the delay. If all decisions involve some degree of delay, do they all involve the same degree of delay? Must all decisions occur in serial order as defined by a single channel system or can more than one occur in the same time unit?

The seven hypothesized processes listed above suggest that in order to be able to organize and to increase the efficiency of the organizing process, the organism must have certain expectancies. The expectancies must exist in three domains, the stimulus domain, the response domain and the domain of time. In the stimulus domain the necessary expectancies pertain to the class of information being transmitted and the modality over which it is being transmitted. If the information is being transmitted visually in the absence of expectancy, the organism may not have his visual receptors properly focused or oriented, resulting in no behavior. If the organism has no expectancy concerning the class of information, identification and discrimination of the specific information will be delayed. Expectancy with respect to the codebook size or the number of alternative stimuli within the class from which the specific event may be selected enhances the ability to respond. Expectancy concerning the stochastic organization of the informational codebook must be reflected in the organisms response family hierarchy in order to increase the probability of a correct response.

The response domain must have expectancies which reflect each dimension of the stimulus expectancies. The S-R relationship is dependent on the mirroring of these expectancy functions.

In the time domain, expectancy with respect to the time of occurrence of the event is essential. If this does not exist, the effector system may be otherwise occupied, thereby either markedly delaying the response or making it impossible. Another dimension in the time domain is related to the stimulus domain. An expectancy must exist for the occurrence of events within the same sense modality and an expectancy must exist for the occurrence of events of different modalities.

It appears therefore that information processing, whether it be on a relatively simple basis as demonstrated in PRP studies or on highly complex levels, is dependent on expectancy to operate at full capacity.

The Expectancy Hypothesis

The original hypothesis. The expectancy hypothesis as an alternative to the PRP hypothesis was first introduced by Hick (1948) and subsequently enlarged on by Poulton (1950) and Elithorn and Lawrence (1955). The expectancy hypothesis proposes that the subject learns the stochastic organization of the time relationships holding between the first and second stimulus in the PRP paradigm, given that the two stimuli are presented over a relatively long series. The delay observed is hypothesized to occur because the subject has a lower expectancy for this class of event with respect to time and is not prepared to respond.

Elithorn and Lawrence take issue with Welford's contention that the expectancy hypothesis merely shifts the question to, "In what does expectancy consist?" They feel that the expectancy approach as conceived by Mowrer (1938) will lead to a better understanding of the time relationships found in PRP studies.

Support for the expectancy position is found in conclusions drawn by May and Bartlett (1963) from a recent study. It was found in this study that the length of the PRP is determined in part by the complexity of the stimulus and response presented to and required from the subject. Complexity represented more discriminations with respect to the stimulus and the response. This increase in number of discriminations indicates an increase in codebook size. If maximum expectancy is equal to 1.0, then an increase in codebook size results in a reduced expectancy for any specific member if all members of the codebook are equiprobable. Hence, following the hypothesis, the subject was not as well prepared to respond to the complex stimulus resulting in an increased time between stimulus and response.

Further support for the hypothesis is drawn from Adams (1962). It is stated that a deduction from expectancy theory which contradicts PRP theory is that, given conditions which allow the acquisition of appropriate expectancies, the human subject can operate as a multichannel system. Adam's study can be interpreted as lending support to this position.

Refraction or expectancy. It appears that the issue between expectancy and refractoriness is clouded by absolutism and definitional problems. The various proponents of the two hypotheses seem to feel that the hypotheses are mutually exclusive. As an example the results of Adams' study are dependent for interpretation on the definition of multichannel.

It is obvious that experiments which have been conducted in support of the PRP hypothesis have all contained ingredients of expectancy. If the subject is presented with a stimulus which is a member of a class which is defined by all possible stimuli to which the subject is sensitive and this class cannot be subclassified, the subject would have virtually no expectancy. If as a result of the above event, the subject had to select a response from a class which was defined by all the responses of which the subject was capable, again expectancy would be virtually non-existant. Under these circumstances the subject's response to the stimulus would be delayed an enormous period of time and it is a question if, in fact, a systematic S-R relationship could be established. Indeed the concept of the S-R bond is grounded on the hypothesis that expectancy must exist.

The concept of refraction cannot be ignored. Incoming information and outgoing effector functions are dependent for transmission on neural networks composed of neurons connected by synaptic junctions. Individual neurons are subject to refraction. Hence neural nets must also have refractory characteristics. The limit of the rate of transmission must inevitably be defined by the refractory characteristics of the neuron nets. This limit however reflects only the maximum rate limit for information processing capacity.

This paper postulates that information processing capacity is a continuum, whose scale points are determined by expectancy. Both expectancy and refraction must be considered in attempting to ascertain the information processing capacity of man. The writer defines this theoretical position as the 'information hypothesis'.

The Information Hypothesis

Information theory and the communication link. It has been postulated above that information processing capacity is a continuum whose scale is determined by expectancy. Expectancy can be described by probability mathematics and thus converted to information measures (Attneave, 1959). Mathematically, information is defined as,

$$H = \log_2 m \qquad [1]$$

where H is information and m is the number of equiprobable alternatives. If the alternatives are not equiprobable, then the information of a specific alternative is,

$$h_i = \log_2 1/p_i \qquad [2]$$

where i equals the i^{th} item of a set m. The information of a specific alternative defined above is often referred to as the 'surprisal' value of the specific item. The average uncertainty or information associated with a source composed of m components of unequal probability is defined as,

$$H = \sum_{i=1}^{m} p_i \log_2 1/p_i \qquad [3]$$

In using information theory as a conceptual model to determine the nature of the continuum of information processing capacity certain points should be made clear. Information as used in this context has nothing to do with meaning. Quastler (1955) has commented that, "Information in information theory is related to such diverse activities as arranging, constraining, designing, determining, differentiating, messaging, ordering, organizing, planning, restricting, selecting, specializing, and systematizing. It can be used with all operations which aim at decreasing entropy, disorder, generality, ignorance, indistinctiveness, noise, randomness, uncertainty, variability, ..."

In this paper the S-O-R relationship is conceptualized as a communication system. The stimulus is an energy change in the environment which impinges on a sense organ, the latter acting in the capacity of an energy transducer. Within the organism reside functions which are analogous to the transmitter, communication channel and receiver of a conventional communication link. The effector response is the behavioral manifestation of the effect of the communication. The communication is transmitted because the behavior is uncertain and the communication should reduce the uncertainty. The system is composed of certain properties which can be related to expectancy and information measures.

Properties of the communication link. The transducers have available to them a great variety of possible messages (stimuli), which vary in their probability of occurrence but which contain some degree of uncertainty. The transmitter transmits a specific message which is unknown to the receiver. This is called an input. The channel includes all equipment used to convey the message, including the transducers and the response. The channel can be composed of many smaller sequential or parallel operating channels. The smaller channels viewed in the aggregate are part of a single communication channel. The channel has its own properties such as filter characteristics, error variance, channel capacity, and noise. Noise is defined as the characteristic within the channel which contributes to variation in the output of the receiver. The response represents the attempt of the receiver to reduce its variance around some optimal point as a result of the information transmitted.

Deductions based on the information hypothesis. Now that a model and a conceptual framework have been developed, some deductions are possible. A reasonable deduction is that the S-R relationship increases as the information of the stimulus and response approaches zero. The stimulus-response relationship is defined operationally as the reciprocal of the time required to make a specific response to a specific stimulus. It has been suggested earlier that expectancy, hence information, operates in three domains in human information processing, the stimulus domain, the response domain, and the time domain. Thus a stimulus-response relationship of maximum value obtains when, (a) the stimulus is known, (b) the response is known, and (c) the time of stimulus occurrence is known, all a priori. Under these conditions the probability for each domain is 1.0, hence the combined probability is also 1.0. If we insert a p-value of 1.0 in the information equation, it is clear that H will equal zero, since the logarithm of 1 is zero. Therefore under the circumstances described, no information has been processed and this situation is of no interest to us.

The maximum relationship between stimulus and response, for the context of information processing, occurs in simple reaction-time studies. Historically, two basic paradigms have been used to perform reaction-time experiments. For one paradigm, the stimulus that will be presented is known, the required response is known, but the precise time of stimulus occurrence following a ready signal is unknown. Thus, we have a probability of 1.0 in two domains, but the probability of the third domain is some value less than 1.0. The degree to which this probability fails to achieve 1.0 is directly related to the number of alternative intervals between ready signal and the stimulus. For the second classic paradigm, the probability in all three domains is 1.0 because there is a fixed foreperiod and the known stimulus always follows the ready signal by a prescribed interval. In the latter case then, there should be no information transmitted. This is not the case. There is some time differential between stimulus and response distributed around zero. This results from the fact that given no other time referent than his own physiological time sense, the subject is not precisely sure of the duration of the foreperiod interval and this uncertainty by definition is information. Hence the probability for all three domains is 1.0 by definition of the experimenter but <u>not</u> by definition of the subject.

Mean reaction-times have been found to be considerably slower when the foreperiod was varied as compared with times measured with a fixed foreperiod. These results are entirely consistent with the information hypothesis. The codebook size with respect to time intervals is larger in the variable foreperiod situation resulting in a lower probability for each member of the codebook and hence greater information which is reflected by increased reaction time.

The information hypothesis sheds an interesting light on the conceptualizations of early investigators in the area of reaction-time studies. The classic arguments concerning the appropriate range of time between foreperiod and stimulus as well as the number of time-range samples becomes in this context an argument over how much information is necessary to ascertain the quickest human response to a signal from the environment. We have taken the position that expectancy must exist. The early experimenters were aware of this because they made both the stimulus and the response known as priori. They even used fixed foreperiods which made time much less uncertain. Then they found that this was producing peculiar results because they were getting anticipatory responses. They decided to reject all responses which could be interpreted as resulting from anticipation. In our context this would be viewed as rejecting a valid sample of responses made in the presence of existing information. The information hypothesis would argue with the philosophical rationale on which the selection of rejectable responses was made. A certain amount of information was presented to the subject for his response. The experimenter then discarded some of the responses which appeared to show the greatest conformity with the information available and accept those responses which appeared to be introducing information which was not present in the stimulus. Hence the experimenter was biasing his results. His mean reaction times showed far greater uncertainty than they would have had he included all the sample. Further, the biasing was unilateral, since the added information consisted of instructions not to anticipate, thereby increasing the uncertainty. If the experimenter accepted latencies of 150-msec. following a 2-sec. foreperiod, S was learning to time 2.150-sec. instead of 2-sec. It is recognized that reaction-time investigators were not interested in information processing. They were attempting to determine the speed of complex neural function on the basis of gross behavioral responses by subtraction, as demonstrated by studies of the A, B, and C reactions (Woodworth and Schlossberg, 1954). The information hypothesis attributes their failure to improper conceptualization as indicated previously. The experimenters defined an artificial state and required of the subject a performance which was atypical.

Recent studies and the information hypothesis. It has been stated previously that due to the inexactness of the organisms time sense, information, which is to some degree time dependent, can never be zero. A study by Adams and Chambers (1962) showed that when stimulus, response and time were all certain by the experimenter's definition, zero reaction time occurred only 22.22% of the time. Hence information was transmitted 77.78% of the time. In this instance zero reaction time was defined arbitrarily as a 33-msec. resolution of the time difference between stimulus and response.

A study of disjunctive reaction time by Mowbray and

Rhodes (1957) challenges the information hypothesis. Mowbray and Rhodes found that disjunctive reaction times to two-choice and four-choice situations could be equated with sufficient practice. A study by Leonard (1954) on the other hand found that there was a lienear relationship between increases in number of alternative stimuli and reaction time. Leonard sampled the range of three and six alternatives. Bartz (1961) found a significant difference in disjunctive response times to 2, 4 and 11 possible stimuli.

In order to resolve these contradictions the following deductions are made. Theoretical considerations of zero and infinite information indicate that the curve describing the relationship between information and the reciprocal of reaction-time must be asymptotic to the ordinate and the abscissa. This follows from the concept that information is never zero but that as it approaches zero, reaction time becomes very small. Likewise if information were very great, approaching infinity, the time required to respond would also be very large. Thus a curvilinear relationship is required and this curvilinearity may account for the equating of reaction-times to 1-bit and 2-bit informational inputs found by Mowbray and Rhodes. It is conceivable that in the range sampled, the results fell on the asymptotic portion of a hyperbola, hence the difference was not sufficient to be significant with the instrumentation used. Leonard's results indicate that a significant difference was found when 2.58-bits of information were presented indicating that the hyperbola at this point deviated sufficiently from zero slope to permit the recognition of the difference.

Channel capacity. In the present conceptual framework, the function of expectancy is to increase what the engineers refer to as channel capacity or the amount of information processed per unit time. This statement is a paradox since expectancy by definition reduces information. Again the problem lies in who is defining information. If from the experimenter's viewpoint the information is not time dependent, he can impose constraints with respect to time which permit him to increase the amount of information in the stimulus domain. A study by Adams and Chambers (1962) used precisely this technique. Stimuli in this study consisted of a stream of simultaneous auditory and visual signals. The codebook size in each dimension was three. One of the members of the codebook was completely certain, hence the codebook size of uncertain events was two for each dimension giving a combined probability for each pair of .25. The inter-stimulus interval between the paired presentations was always 2-sec. Thus in this study we have event uncertainty but time is constrained in two dimensions; time is constant between events of the same modality and time is certain between events of different modalities. Thus no information was transmitted with respect to time from the experimenter's viewpoint although the 2-sec. interstimulus interval contained some information from the subjects viewpoint due to his inexact time sense. The simultaneity of the presentations transmitted no time information between modalties since the subject rapidly learned that whenever a visual stimulus occurred it was accompanied by an auditory stimulus.

Graphic description of time-on-target scores in the study show that bisensory performance suffered a decrement when compared with unisensory performance. Examination of the detailed data indicated that this difference was not due to a difference in response time but rather it was due to the larger number of errors committed in the bisensory situation. An analysis of variance indicated that the trials effect was significant at the end of training suggesting that the errors might have been eliminated with more training. Bisensory responding did not slow down the subjects' ability to respond.

Auditory response conformed to previous findings in the unisensory situation and was significantly faster than visual response. There was no significant difference between response times of responses made to unisensory visual stimulation or bisensory visual stimulation. The response to auditory signals when paired with visual signals was slowed down to the pace of the visual signal response. These results can be interpreted to indicate that the time constraints were necessary for the processing of the information. If the organism had not been dependent on the simultaneity of the presentations the responses would have maintained the same speed relationships which existed in the unisensory situation. The fact that they did not indicates that simultaneity was a necessary condition in the response domain.

A recent study by Creamer (1963) is further evidence for the function of expectancy and the necessity of constraints. Creamer presented auditory and visual stimuli which had time certainty but not event certainty. Hence his conditions at this level of description were identical with those of the Adams and Chambers study. Creamer, however, changed the time-certain configuration. The stimuli of different modalities did not occur simultaneously but were separated by constant time periods ranging from o-msec. to 800-msec. The auditory stimulus was always the second stimulus. Under these time-constant conditions, Creamer's results showed that there was an increase in response times for interstimulus intervals of 400-msec. or less. It can be argued that due to the inexact time-sense of the human organism, time-certainty is not a sufficient constraint to permit the processing of information without decrement. When the occurrence of an event in one dimension did not also signal the occurrence of an event in another dimension, the amount of information transmitted was increased. The initial signal, under these conditions became a ready signal which had the further complexity of requiring decoding and response. The information in the time domain was increased in the same fashion that it was in classical studies of disjunctive reaction time. The information hypothesis contends that this increase in information was beyond the limit of the capacity of the organism to respond without decrement.

Single channel or multi-channel? It has been indicated that PRP hypothesis implies that the human organism is a single channel information processing system. The expectancy hypothesis implies that the organism is capable of multi-channel operation given adequate expectancies. Multi-channel has been in the past associated with the form of the energy impinging on the transducers. Regardless of how the energy entered the system, multi-channel operation does not exist unless the channels are maintained separately throughout the system. The evidence cited indicates that this is not the case. The information hypothesis contends that the organism is capable of processing a specific amount of information per unit of time. For a given unit of time, the quantity of information which is within the limits of the processing capacity of the system may enter the system over one or more transducer sub-systems. But, when the quantity of information entering the system, whether it be over one transducer or more, exceeds the limit of the processing capacity for that time unit, it becomes a member of the processing capacity population of the next larger time unit.

Thus, the information hypothesis, although based on expectancy, does not lead to the same conclusions derived from the original expectancy hypothesis. In addition, the information hypothesis is not limited to the lower limit of the information processing continuum as is the PRP hypothesis, but claims the capability of expressing the relationship of time and information over the entire scale.

<u>The adequacy of the definition of information</u>. Information, as it has been defined, has been based entirely on the determination of probabilities which in turn were derived from relative frequencies of event occurrence. Inherent in this concept is the fact that discrimination between different events must be possible in order to permit the distinction of the relative frequencies. Hence, response time will go to infinity when the number of discriminations required of a particular sense modality exceed the capacity for discrimination of that modality. It follows, then, that the parameter of the sense modality over which the information is being transmitted must be entered in the equation in the proper value for the adequate prediction of the time-information relationship.

It has also been noted that experimenter-defined probabilities may not necessarily conform to those of the subject, particularly in the time domain. This situation may also obtain in the domains of stimulus and response. Events which may be viewed by the experimenter as unitary and given a probability as a unit, may have components which themselves have a relative frequency organization. If this situation exists, the probability values of the event must be weighted by these probabilities.

The Study. The following study attempts to shed light on the adequacy of the information definition. The study imposes constraints with respect to time while varying the modality of input presentation. Regardless of input modality, the amount of information per unit input remains constant both with respect to event occurrence and time. The response domain, likewise, is constant throughout the study. Thus we are examining the relative character of two sense modalities, auditory and visual, and further, we will examine the effect of what Titchener called 'the stimulus attributes' (Boring, 1942) on human information processing capacity.

CHAPTER III

METHOD

The strategic approach to the problem will be as follows. The information in terms of event occurrence will be constant throughout all conditions. The response required will be constant throughout all conditions. Independent stimuli will be presented simultaneously through separate sensory transducers both within and across sensory modalities. In addition one condition will contain a single source stimulus which contains the same amount of information as that presented by the simultaneous paired stimuli used in the other conditions. The effect of various stimulus parameters will be the primary goal of this research.

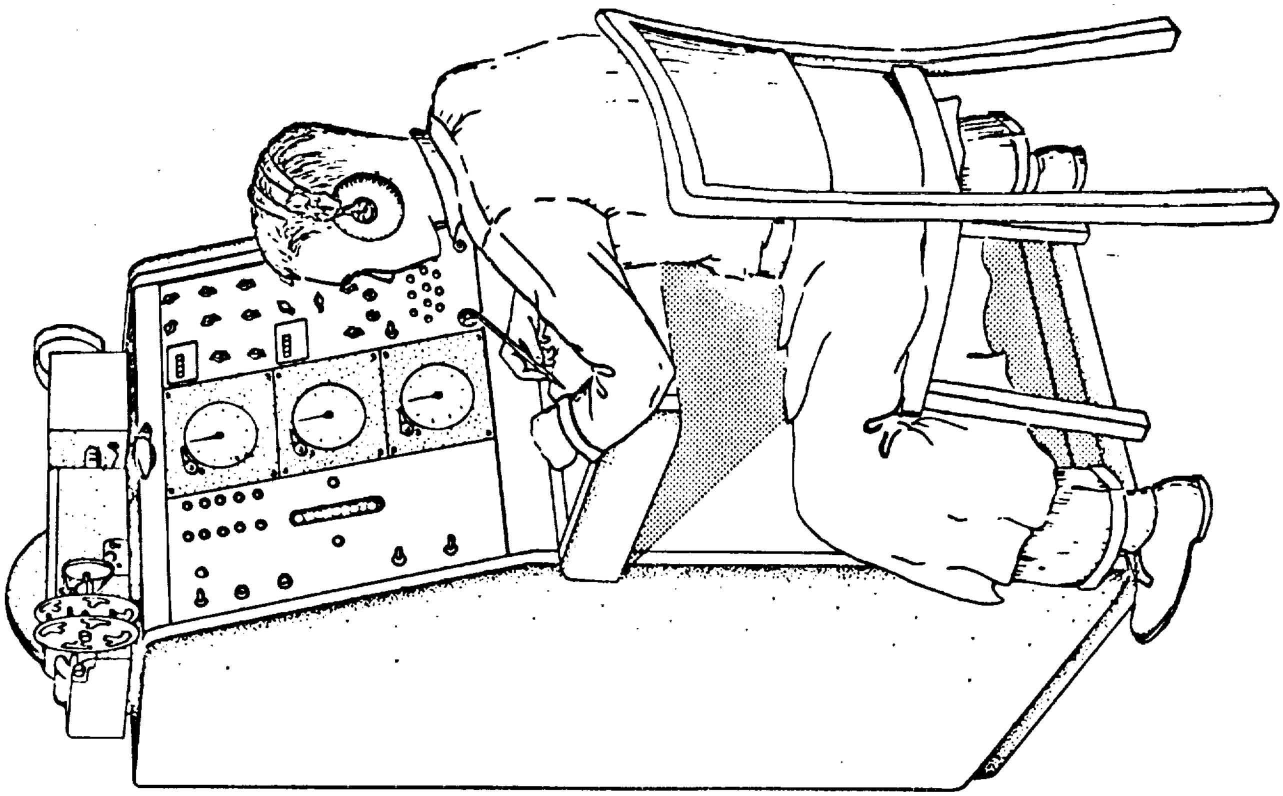
Apparatus. The device used was the Bisensory Unilateral Response Processor (BURP) which was designed by the author to examine the following variables pertinent to information processing as reflected by psychomotor responses; probability of event occurrence, probabilities with respect to time, complexity in terms of codebook size and in terms of information contained in a signal, rate of flow of information, number of units of information presented in the same time unit and comparison of unisensory versus bisensory information processing. BURP is a fully automated electronic devise and measures information processing capacity in terms of the time differential between stimulus and response for both left and right hand responses.

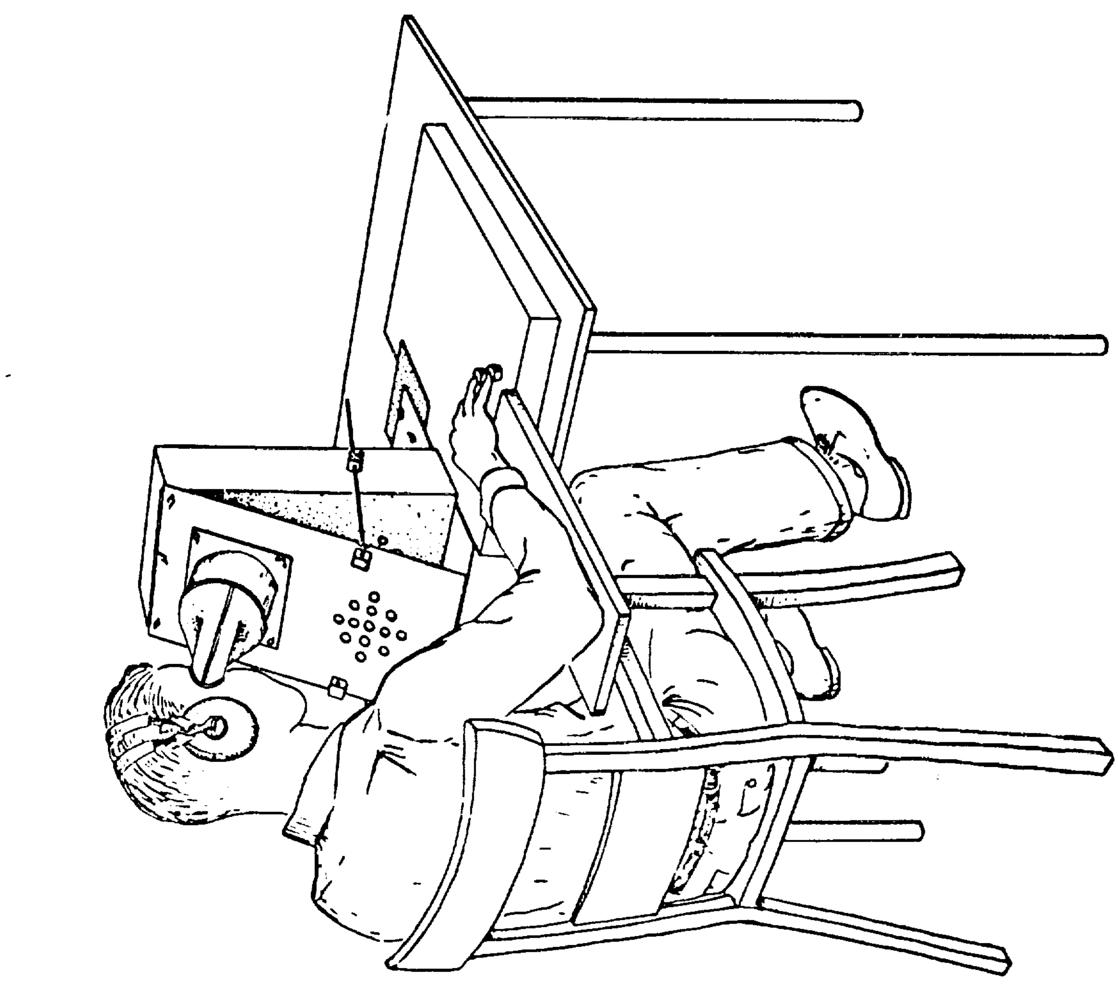
An external view of the major components of BURP is shown in Fig. 1. In the normal experimental situation, S's response panel and displays, shown on the left of Fig. 1, are separated from E's control console, shown on the right, by placing each in a separate room and connecting the two by cable. The S components shown above are: a 10-key response panel, a dismountable visual display which is viewed by S through a hood, earphones for auditory displays, and a chair with adjustable arm supports. The control console contains power supplies, switching matrices, 10 audio-frequency oscillators, timing system, binary converter system, a display panel showing timing clocks, counters, monitoring feedback lights, programming control switches, output tape punch, input tape reader, and an intercommunication unit. Fig 2 shows a block diagram of the basic units comprising the total system and the cabling relationships holding within the control console and between the console and S's unit.

S's unit consists of a 10-kay response panel divided into 2 units of 5 keys each, one for each hand, and 3 displays, 2 visual and 1 auditory. It is shown in detail in Fig. 3. The response manipulanda are composed of 10 microswitches which are activated by 10 pushbuttons. There is 1 pushbutton for each of the 10 fingers and they are arranged on the chassis for S's maximum comfort. Each microswitch has an adjustable screw setting which permits equating all switches in terms of amount of throw necessary for activation. The spring return on the switches has also been equalized. The pushbuttons are aluminum discs which have been turned and cupped to provide firm contact with each finger under the stress of relatively high speed responding. Each set of 5 pushbuttons is mounted in a separate chassis; the two chassis are coupled together by a slotted cast-aluminum plate. This arrangement permits sliding the two units closer together or farther apart to achieve maximum operating position comfort for the hands of individual S's. Wing nuts fasten the chassis in the selected position. The left hand chassis contains a warning buzzer which is activated during experimental sessions by the programmed tape and is used to alert S to the imminent occurrence of a series of signals.

The visual displays are interchangeable and are mounted on 1/8-in. aluminum plates which are hinge-mounted to a vertical support chassis. The vertical support chassis is connected to the pushbutton response chassis by a slotted cast-aluminum plate permitting forward-backward movement of the chassis. This movement flexibility in conjunction with the upward swing of the hinged display plate permits positioning of the headrest of the viewing hood for the

Fig. 1. BURP. S's unit is on the left and E's control console is to the right.

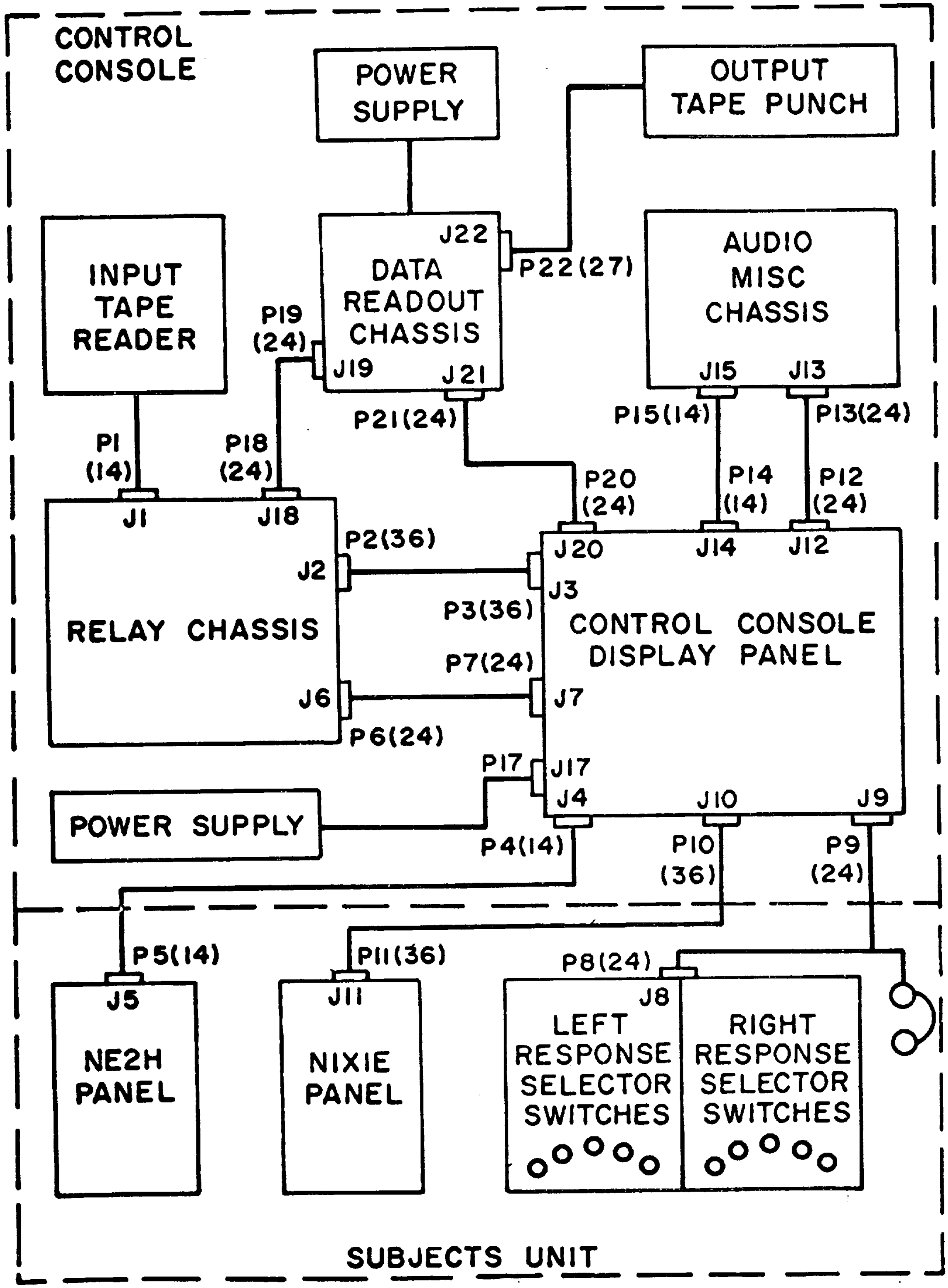




maximum comfort of any S and reduces the probability of fatigue-induced distortions of S's performance due to fixed position over time. Since S and E are separated in the experimental situation, communication is effected by a built-in intercommunication system. The loudspeaker for S's unit is mounted in the lower half of the vertical support chassis and is completely controlled by E, permitting E to hear S at all times but allowing S to hear E only if the latter pushes a press-to-talk button.

The visual display shown on Fig. 3 replaces the display described above and is mounted on the same hinged support. The viewing hood is transferred complete with bezel to this display but under this condition the septum is removed, permitting S to view the entire display binocularly. The display consists of a vertical column of 5 miniature Nixie tubes, Model 7009. On either side of the column at the center is mounted a single Ne2H bulb whose activation or deactivation provides feedback to S relative to the correctness of his right and left hand responses. The Nixie tubes are wired to display numbers 1 through 5 each at the discretion of the program. The left hand pushbutton system is relevant to which number is displayed and the right hand pushbutton system is relevant to the columnar position of the Nixie displaying the number, with Position 1 being at the top of the column and Position 5 being at the bottom. Thus if the number 5 is displayed by the Nixie in Position

Fig. 2. Block diagram showing component units of BURP.

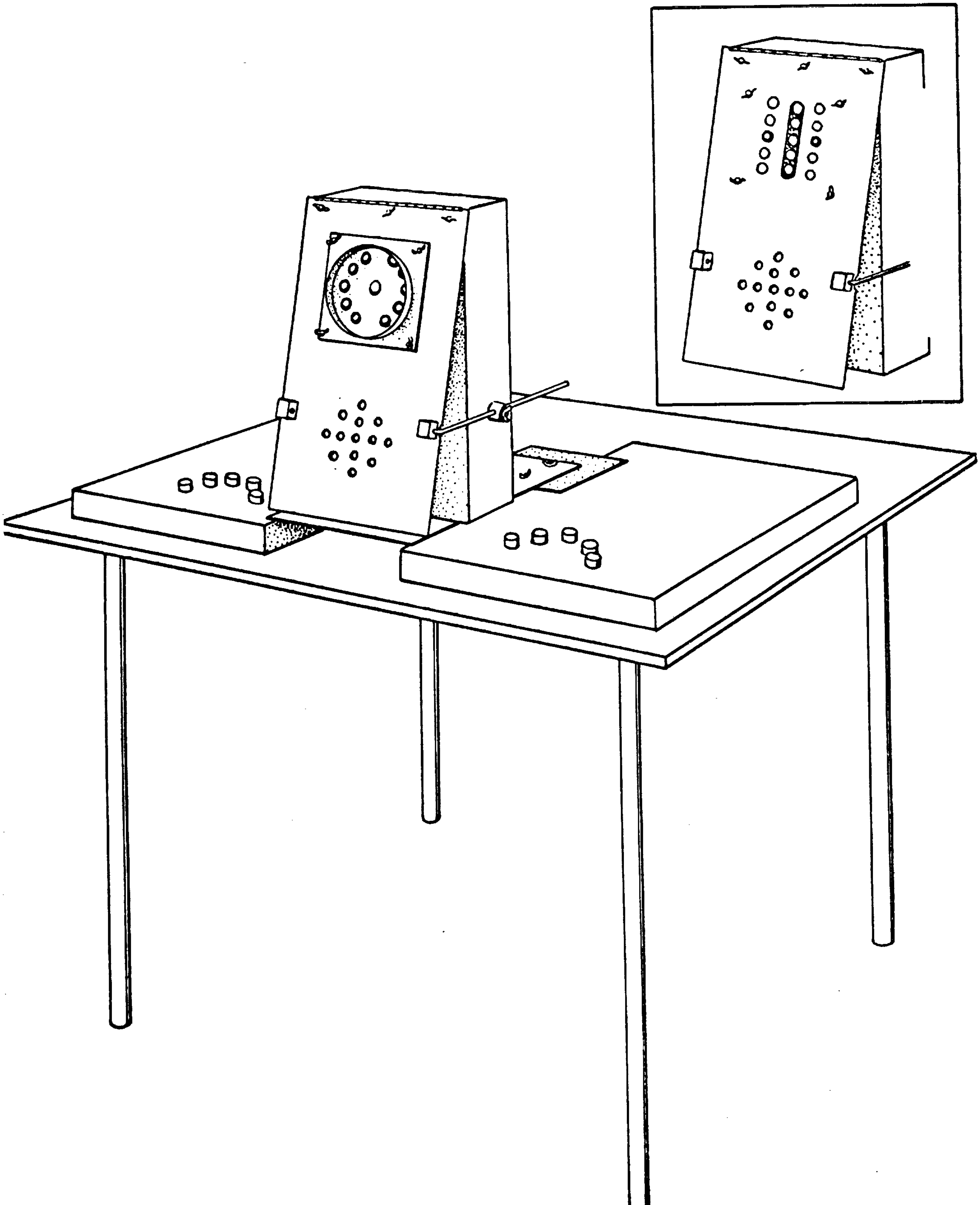

CONTROL CONSOLE
POWER SUPPLY
OUTPUT TAPE PUNCH
INPUT TAPE READER
DATA READOUT CHASSIS
J22
P22(27)
AUDIO MISC CHASSIS
P19 (24)
J19
J21
J15
J13
P21(24)
P15(14)
P13(24)
P1 (14)
P18 (24)
P20 (24)
P14 (14)
P12 (24)
J1
J18
J20
J14
J12
P2(36)
J2
J3
P3(36)
RELAY CHASSIS
CONTROL CONSOLE DISPLAY PANEL
P7(24)
J6
J7
P6(24)
P17
J17
J4
J10
J9
POWER SUPPLY
P4(14)
P10 (36)
P9 (24)
P5(14)
P11(36)
P8(24)
J5
J11
J8
NE2H PANEL
NIXIE PANEL
LEFT RESPONSE SELECTOR SWITCHES
RIGHT RESPONSE SELECTOR SWITCHES
SUBJECTS UNIT

2, a correct response by S would be pressing the button with the left hand assigned to the number 5 and pressing with the right hand the button assigned to Position 2. If the left response is correct the left Ne2H bulb extinguishes and if the right response is correct the right Ne2H bulb extinguishes. When both are correct the entire display extinguishes.

The auditory display consists of 10 tones and is presented to S through a high impedance Roberts stereo-headset, model 5404, which plugs into a jack mounted on the left response chassis. The stereo-headset can present at the discretion of the program any one of the following tones to the left ear: 350,600,1250,2500,5400 cps. The tones presented to the right ear are: 250,450,900,1700,3500 cps. The tones are generated by 10 oscillator systems and are processed through 2 pre-amplifier systems. The 5 left hand pushbuttons can be assigned to any of the left tones and the 5 right hand buttons to any of the right tones.

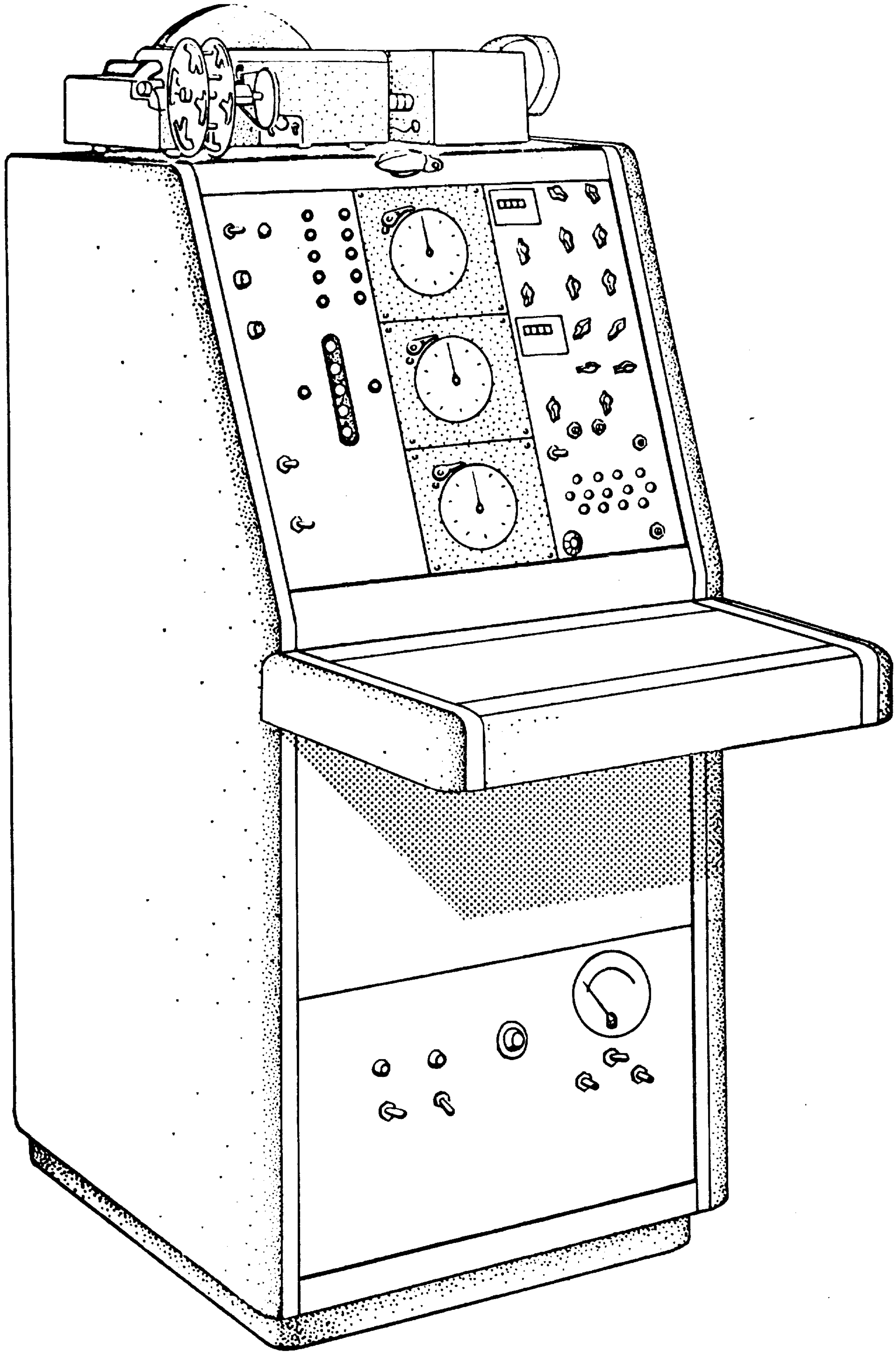
The wiring net relating stimulus and response events, the systems providing performance records, and the controls which provide flexibility in the device are located in E's control console which is shown in Fig. 4. The occurrence of stimuli is dictated by a programmed punched tape into an electronic switching matrix by a California Technical Industries tape reader, Model 220. The time relationships holding between stimulus events, both serially and between

Fig. 3. _S_'s unit showing response units, Ne2H display mounted and Nixie display in inset. Viewing hood has been removed.



stimulus events, both serially and between independent left and right systems, can be controlled by both the positions punched on the tape and the nature of a cam used on a constant speed synchronous motor which activates a switch and pulses the feeder mechanism of the reader. This system provides complete freedom in the determination of stimulus time functions as well as a high degree of precision. In addition to activating S's display, the matrix activates E's visual monitoring feedback systems located on the left side of the console display panel providing information relative to the proper functioning of the device. Auditory monitoring is provided for E by a headset similar to S's which plugs into a jack on the right side of the panel. The matrix also activates the two data readout systems, one of which is composed of 3 Standard Electric time clocks and 2 Veeder-Root counters, the other system being an individual response timing mechanism whose output is binary-coded on paper tape by a Friden 8-channel tape punch. The 3 clocks are used to cumulate reaction time for each of the left and right systems, with the third clock cumulating for bimanual function over a series of stimulus presentations. The clocks are activated with the onset of stimuli and shut off either as a result of a correct response by the appropriate response system or the termination of the stimulus duration. Thus, general measures of both right

Fig. 4. *E*'s control console. Tape output punch is at the top left and reader is on the right. From left to right are control switches, monitoring visual display, time clocks, correct response counters, 2 Stimulus Modality Switches between counters, 10 Task Program Switches, 2 Information Coding Switches and intercommunication unit.



and left hand responses as well as both in combination are reflected by the 3 clock readings. If no correct responses are made over a 90-sec. trial the clocks will cumulate 90 sec. Any time less than 90 sec. represents the time savings provided by the speed and accuracy of the responses. The Veeder-Root counters cumulate the number of correct responses in each system over a trial. A correct response is defined as the pressing of the button assigned to a particular stimulus within the period of the stimulus duration. Feedback to S with respect to the correctness of his response is provided by the termination of the stimulus following the response when the response is correct. In order to prevent S from being scored for a correct response which he might achieve by pressing all keys simultaneously or by executing a high speed sequential finger roll, S always operates on a non-corrective basis. An automatic clock and counter-reset switch is located to the right and opposite the bottom clock, permitting the reset of all these units in a single motion.

The right of the two counters have two columns of 5 rotary switches, each with 5 positions. These switches represent the 5 stimuli in each system, right and left. The 5 positions represent the 5 pushbuttons in each system. By setting these switches prior to S's experimental session, E determines which pushbutton is related to which signal. This also permits making one pushbutton relevant to more than one signal or one signal relevant to more than one pushbutton. This switch system is named the Task Program Switch system. Located between the 2 counters are the Stimulus Modality Switches which E uses to establish which of the three possible stimulus modalities will be presented to S, Ne2H, Nixie, or Auditory. Since the two systems are independent, E can have the stimuli occurring bisensorally by placing one switch on Ne2H and the other on Auditory.

At the bottom right of the display panel is E's intercommunication system. Master control switch and indicator lamp, component control switches and fuses are located in a column on the extreme left of the display.

Experimental procedure. The design used was a counterbalanced Latin Square, in which the 4 Ss trained in every condition in counterbalanced order. The conditions were, VV or the simultaneous presentation of independent visual signals, one in each eye; AA or the simultaneous presentation of independent auditory signals, one in each ear; AV or the simultaneous presentation of independent auditory and visual signals, the visual signal in one eye and the auditory signal in the opposite ear; NN or the binocular presentation of a number on a Nixie tube. The number presented and the position of the Nixie in which the number occurred were independent and were the code used as has been described in the apparatus section. Response manipulanda consisted of pushbuttons, with one assigned to each signal in any given condition. In this experiment the number of alternative stimuli presented for response by each hand was 3, allowing a maximum of 9 possible combinations in any given condition. Stimuli occurring on the left were always responded to with digits of the left hand and stimuli occurring on the right were always responded to with digits of the right hand. In Condition NN, the left hand coded the number and the right hand coded the position of the tube displayed. Condition AV was counterbalanced among the 4 Ss, making 2 Ss perform AV and the other 2 Ss perform VA.

Trials were of 90-sec. duration and consisted of 90 pairs of 1-sec. events. Events occurred continuously with no dead time between events. The termination of a pair of stimuli was accompanied simultaneously by the onset of a new pair of stimuli. Subjects practiced for not less than 4-hrs. in each condition. In some cases as much as 10-hrs. practice were expended on the same condition. Each 1-hr. of practice represented 20-trials, or 3600 responses. The inter-trial rest interval was 40-sec., except between trials 10 and 11 of each 1-hr. practice session, when S was allowed a 5-min. rest. All events and rest periods were programmed on punched tape and proceeded without intervention from E. Scoring was recorded at the end of each trial by E from the 3 Standard Electric Time Clocks. As indicated in the apparatus section, 1 clock recorded the time for the left hand, 1 clock recorded the time for the right hand and the third clock represented the time reflected by the bimanual response. All 3 clocks were initiated by the occurrence of a pair of stimuli and continued to run until S made the correct response. If S either made an incorrect response or failed to respond, the clocks continued to run for the 1-sec. of the stimulus duration. Since, however, the termination of 1 stimulus was accompanied by the initiation of another stimulus, if S failed to respond throughout a trial, the clock would cumulate 90-sec., the length of the trial. Thus any time recorded on the clock which was less than 90-sec. represented the speed and accuracy of S's responses. The mean correct response time for individual responses can be calculated by subtracting 1-sec. from the total trial score for each error or ommission and dividing the balance by the number of correct responses. The number of correct responses for each hand were summed over a trial by two counters and were also recorded at the end of the trial by E.

As has been indicated, each system, right and left hand, in every stimulus condition, required 3 responses, 1 to each of 3 possible alternative stimuli. The 3 stimuli in each system were equi-probable and were generated independently from a table of random numbers. Thus, the intra-hand stimuli each had a probability of occurrence of .33

and the dual-hand probability was approximately .10 for any given stimulus pair.

The 4-Ss were all students at the University of Arizona and were paid on an hourly basis for their participation in the experiment. Two were males and two were females. Pre-training practice in single-handed operation was given all Ss prior to dual-handed function. Each S was trained single-handedly for both hands in each condition until he had achieved 5-trials in a row without error, for each hand. Instructions consisted merely in telling S to respond as quickly and accurately as possible to the stimuli. Since S had had the pre-training in single-handed operation, he was aware of which button was appropriate for each stimulus in the dual-handed training. Compatibility between stimulus and required response was maintained such that in VV, the light at the top left was designated as Light 1 for the left system and was responded to by the thumb of the left hand. The next position down was Light 2 and was responded to by the index finger. The next position was Light 3 which required a response by the middle finger. The same configuration held for the right hand system. In AA, tones were differentiated by pitch, as indicated in the apparatus section, with low corresponding to thumb and so on. Response to the AV condition was a combination of the VV and AA responses. In NN, the 1, 2, and 3 corresponded to thumb, middle, and index finger of the left hand, while positions 1, 2, and 3 corresponded to thumb, index and middle finger of the right hand. Position 1 was at the top of the column of Nixies and 3 was at the bottom.

All Ss were separated from E during the experimental and training sessions. The Ss performed the task in a sound-deadened shielded booth, which measured 95" x 49" x 74". The booth was constructed of 2" x 4" framing covered both inside and out with acoustic tile. The space between the inside and the outside tile layers was filled with fibre glass insulation. In addition to the door, the booth had a 24" x 24" one-way-vision viewing window, which permitted E to view S at all times without S being aware of E's presence. Lighting in the booth was controlled by a variac unit and ventilation was provided by a squirrel-cage exhaust fan operated through a 4" muffled ducting system. The control console was outside the booth so that any cues provided by relay sounds or the control panel feedback monitoring displays were not available to S.

CHAPTER IV

RESULTS

The performance of each S in all conditions is shown in Figs. 5-8. The order of learning of each condition is reflected by the order of code designation on each figure. Subject 1 learned in the order, AA, VV, AV, NN; Subject 2 in the order, VV, AA, NN, AV; Subject 3 in the order, NN, VA, AA, VV; and Subject 4 in the order, AV, NN, VV, AA. Learning is shown as the reciprocal of the mean cumulated response time ($R_{1/t}$) for correct responses plus a penalty of 1-sec. for any erroneous or ommitted responses, as explained in the procedure section. $R_{1/t}$ is shown as a function of the number of 5-trial blocks (N). It is immediately apparent that Ss practiced the different conditions for varying periods of time. The variance in practice time was dictated by several factors including time availability, general level of skill of individual Ss, S motivation, etc. In any case there are some profitable conclusions to be drawn with respect to performance under the various conditions. First, it is apparent that all Ss achieved their most capable performance under condition VV and their poorest under Condition AA. Further, learning on Condition AA was virtually nonexistent for all Ss. This was also evident in the case of Subject 1, who practiced AA for 9-hrs. or 32,400 responses. In all cases the level of performance at the end of training in Condition AA is not equal to the level of performance reflected by the mean response time for the first 5-trial block on VV. A reasonable conclusion from the above is that in the time parameters used, response to AA is beyond the capabilities of the human organism. Another point of interest is that neither condition containing auditory function shows any positive transfer from S's previous experience with the stimuli and/or the response. Subject 1 shows some positive transfer to VV from AA but negative transfer to NN from VV and AV. The positive transfer in this case is probably not transfer at all but rather an indication of the fact that, as it was for all Ss, VV was initially easier. Subject 2 shows virtually no transfer in any condition and Subject 3 shows positive transfer in the case of VV only. The wide margin favoring VV in the first 5-trial block shown by Subject 3 may be a combination of positive transfer, VV being the last condition learned by this S, and the greater facility all Ss demonstrated in this condition. Subject 4 shows positive transfer to NN from AV but negative transfer to VV from NN. Certainly transfer is not a systematic function in this study.

Subjects 2 and 4 show the same ordering of skill both in acquisition as well as final performance. VV for these 2 Ss is the most learnable and produces the fastest

Fig. 5. Reciprocal of mean cumulative response time in .001-min. plotted as a function of 5-trial blocks for Subject 1. The parameters are conditions. The times were taken from the total clock which reflected the speed and accuracy of both hands. The order in which Subject learned the conditions is reflected by the order of the parameter identification code on the drawing.

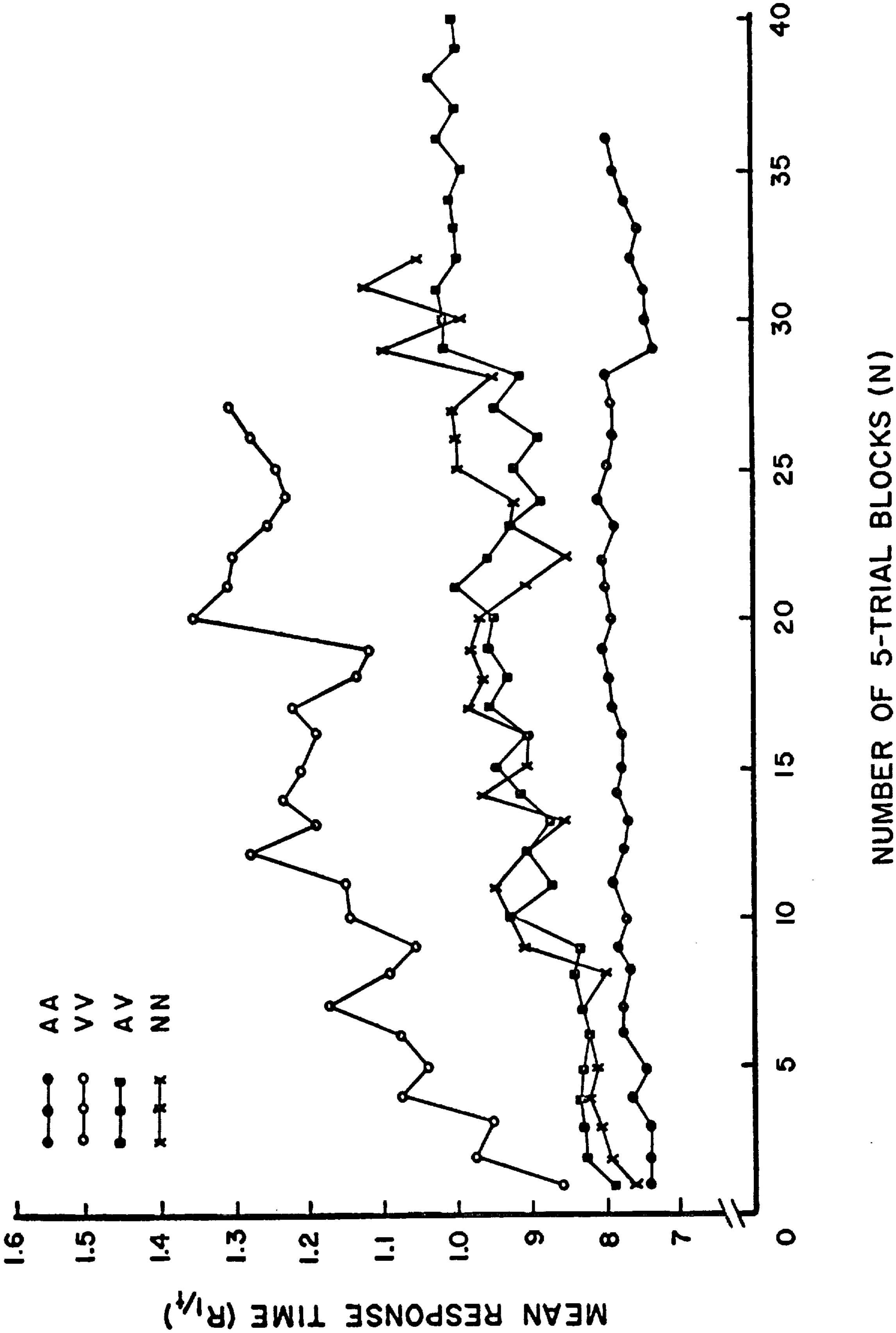

AA
VV
AV
NN
MEAN RESPONSE TIME ($R_{1/t}$)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
0
5
10
15
20
25
30
35
40
NUMBER OF 5-TRIAL BLOCKS (N)

Fig. 6. Reciprocal of mean cumulative response time in .001-min. plotted as a function of 5-trial blocks for Subject 2. The parameters are conditions. The times were taken from the total clock which reflected the speed and accuracy of both hands. The order in which Subject learned the conditions is reflected by the order of the parameter identification code on the drawing.

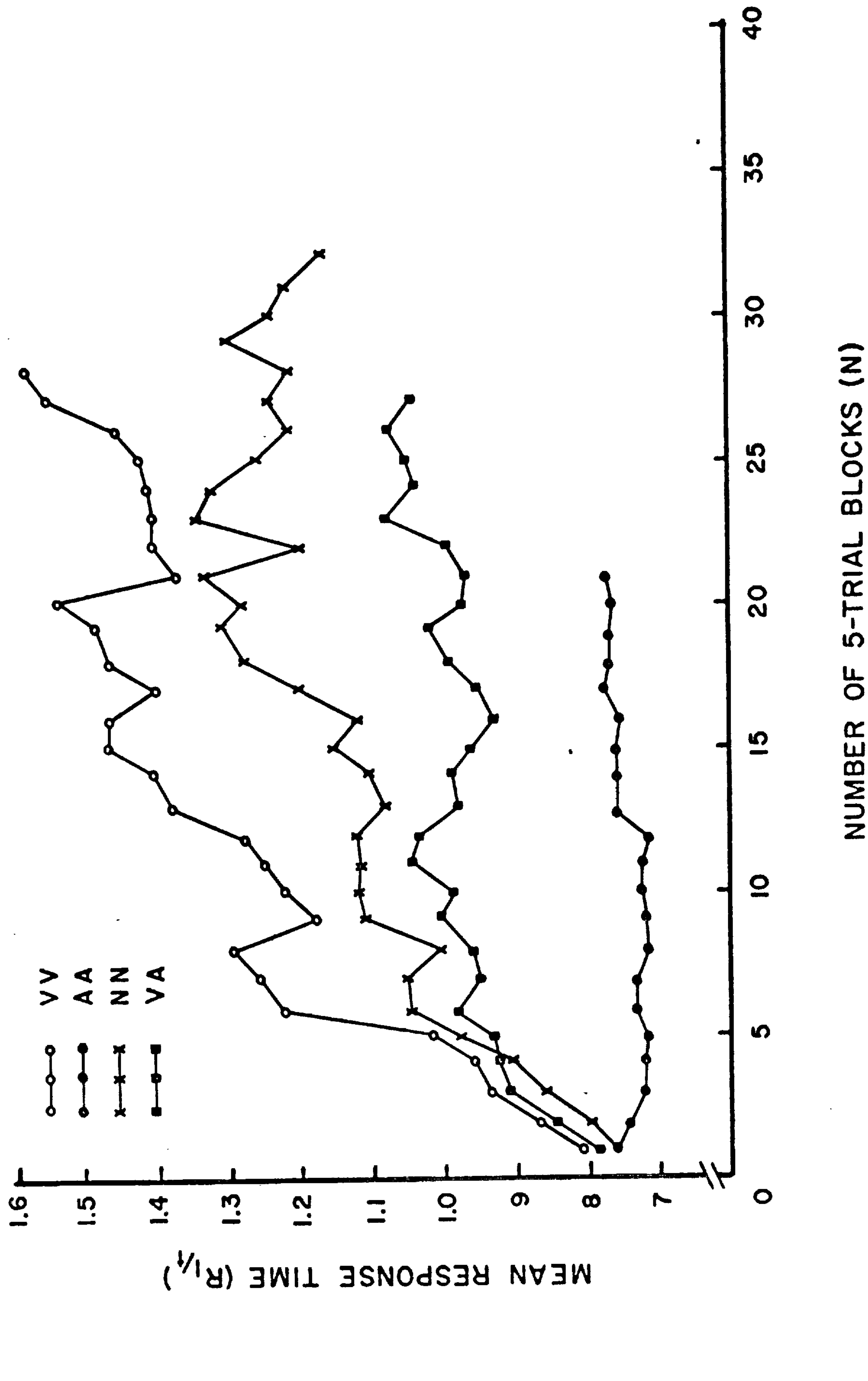

VV
AA
NN
VA
MEAN RESPONSE TIME ($R_{1/1}$)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
0
5
10
15
20
25
30
35
40
NUMBER OF 5-TRIAL BLOCKS (N)

Fig. 7. Reciprocal of mean cumulative response time in .001-min. plotted as a function of 5-trial blocks for Subject 3. The parameters are conditions. The times were taken from the total clock which reflected the speed and accuracy of both hands. The order in which Subject learned the conditions is reflected by the order of the parameter identification code on the drawing.

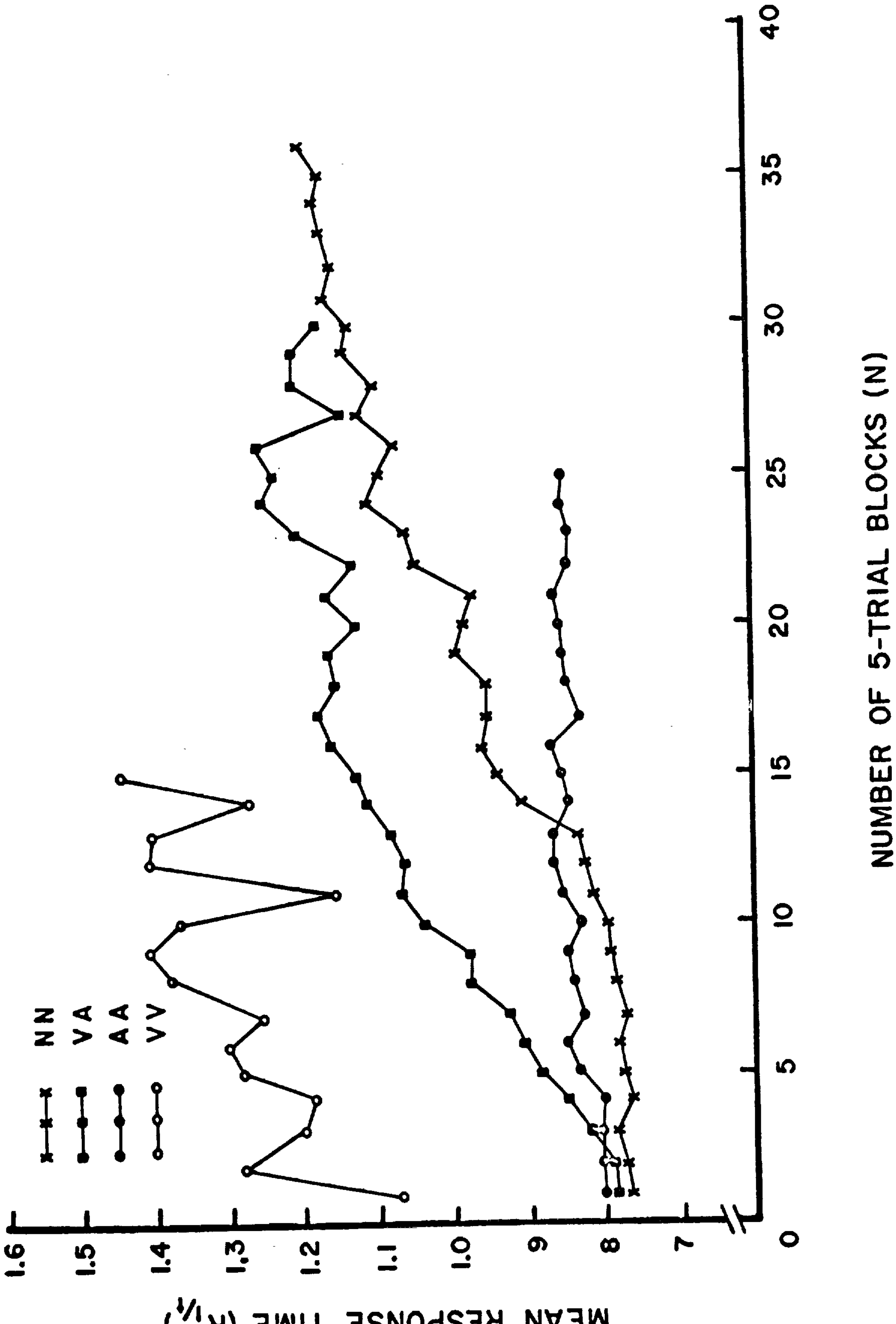
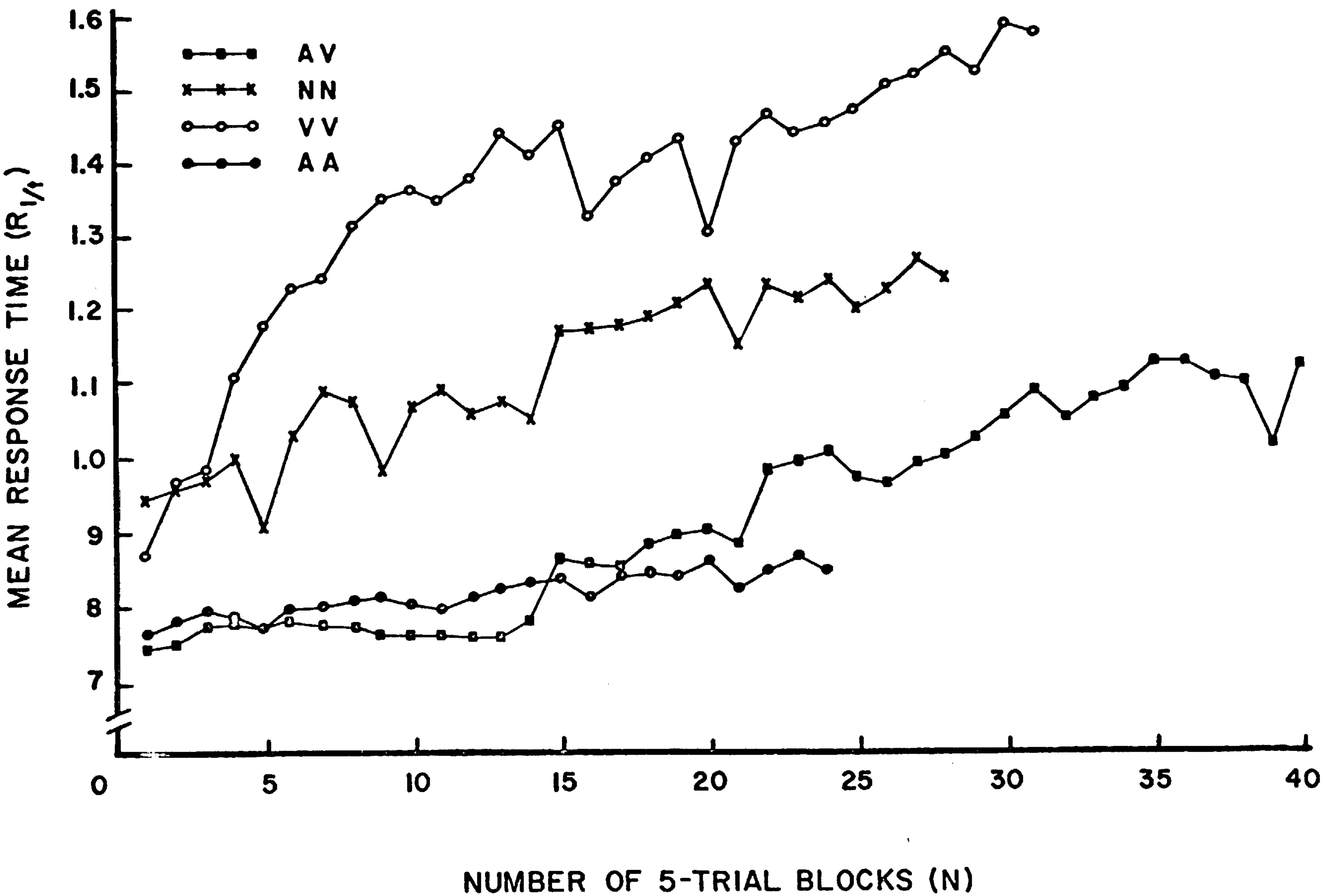

NN
VA
AA
VV
MEAN RESPONSE TIME
NUMBER OF 5-TRIAL BLOCKS (N)

Fig. 8. Reciprocal of mean cumulative response time in .001-min. plotted as a function of 5-trial blocks for Subject 4. The parameters are conditions. The times were taken from the total clock and reflected the speed and accuracy of both hands. The order in which Subject learned the conditions is reflected by the order of the parameter identification code on the drawing.



AV
NN
VV
AA
MEAN RESPONSE TIME ($R_{1/t}$)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
9
8
7
0
5
10
15
20
25
30
35
40
NUMBER OF 5-TRIAL BLOCKS (N)

performance. NN follows next in acquisition and skill, with AV and AA following in that order. Subject 1 shows a tendency for the same ordering at final skill level, although during acquisition NN and AV overlap to such a degree that the superiority of NN over AV cannot be stated unequivocally. For Subject 1 as well as for Subject 3, the superiority of VV and the inferiority of AA is as apparent as for Subjects 2 and 4. Subject 3 adds real confusion to the NN/AV relationship by showing superior acquisition and skill on AV. In view of the performance of Subjects 1, 2, and 4, it seems that the order of skill level VV, NN, AV, AA, may reflect the general learning characteristics for these conditions in the population.

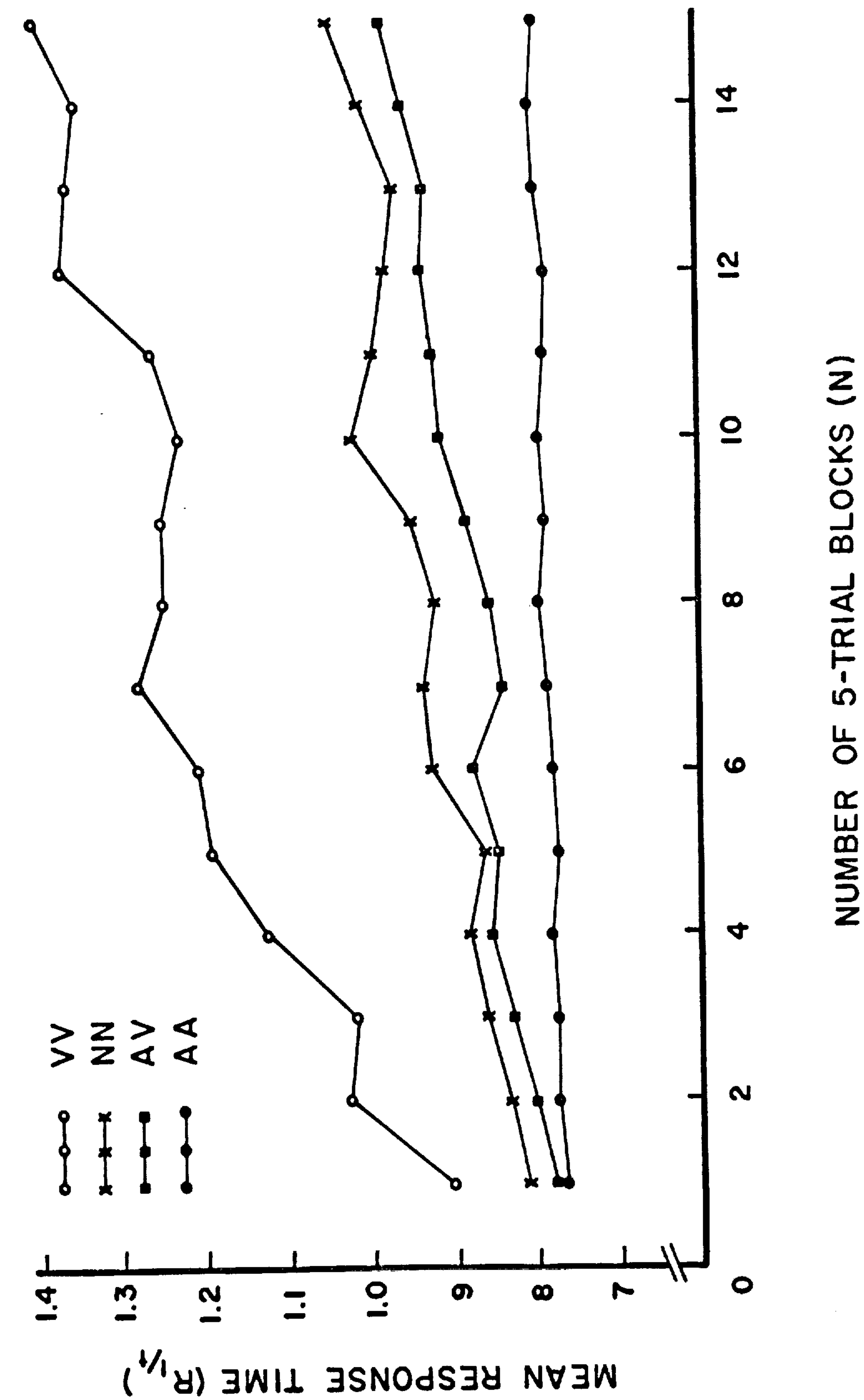
An analysis of variance in terms of trials x conditions x subjects was computed over Trial Blocks 1-15 as shown on Fig. 9. Cell scores were composed of the mean $R_{1/t}$ of each S for each 5-trial block. As a result of the counterbalanced design, it was possible to combine Ss' scores for each condition for each trial block. The results are shown in Table 1.

TABLE 1

SUMMARY TABLE FOR ANALYSIS OF VARIANCE

Source	df	Sums of Squares	Mean Square	F	P
Between Subjects	3	.222	.074		
Within					
Trials	14	1.063	.076	2.303	.01> p<.05
Conditions	3	6.794	2.265	2.841	NS
S X T	42	1.375	.033		
C X T	42	29.986	.714	9.780	p<.01
C X S	9	7.177	.797		
C X S X T	126	9.235	.073		

Fig. 9. Reciprocal of mean cumulative response times in .001-min. for all <u>S</u>s taken from the total clock plotted as a function of 5-trial blocks. The parameters represent the 4 conditions of practice.


VV
NN
AV
AA
MEAN RESPONSE TIME ($R^{1/4}$)
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
0
2
4
6
8
10
12
14
NUMBER OF 5-TRIAL BLOCKS (N)

The S X T interaction was used to evaluate the trials effect and the C X S interaction was used as the evaluation term for the conditions effect. The C X S X T second order interaction was used to evaluate the T X C interaction. The significant trials effect indicates that through Trial Block 15, learning was still taking place. The fact that the conditions effect was not significant can be accounted for by the between Ss variance and the fact that the variance ratio contained only 3 and 9 degrees of freedom, the penalty one pays for using a small number of Ss. The important factor for our purposes is that the C X T interaction was significant beyond the .01 level. This interaction indicates that in fact Ss were learning differentially as a function of the training conditions. Only 15 trial blocks could be used for this analysis because Subject 3 became unavailable after having completed only 15 trial blocks of practice on VV. This state naturally imposed the limit on the number of trial blocks which could be used for grouped data with respect to acquisition.

In order to determine the effect of conditions as well as the difference between conditions at skilled practice levels, a test of orthogonal comparisons was used to examine and compare the scores for all Ss taken from the total clock. Each score for each S was taken at that trial block value which was the point of maximum practice in the condition in which they achieved the least practice. For

Subject 1, this was Trial Block 27. For Subject 2, this was Trial Block 21, for Subject 3, Trial Block 15, and for Subject 4, Trial Block 24. The results of this test are shown in Table 2.

TABLE 2

SUMMARY TABLE FOR CONDITIONS AT SKILLED PRACTICE LEVELS

Source	df	Sums of Squares	Mean Square	F	p
Between Subjects	3	.081	.027	1.928	NS
Within					
Conditions	3	.757	.256	18.286	$p<.01$
VV-NN/AA-AV	1	.503	.503	35.92	$p<.01$
VV/NN	1	.190	.190	13.57	$p<.01$
AA/AV	1	.063	.063	4.50	NS
Error	9	.125	.014		

The results indicate that difference in performance between Ss was not significant despite the difference in the trial block from which they were selected The effect of conditions, however, was significant, indicating that Ss were performing differentially as a function of conditions. The results also show that the performances which had entirely visual inputs were significantly superior to the performances which were dependent to some degree on auditory inputs (VV and NN compared with AV and AA). The VV/NN test shows that VV was significantly superior to NN. The last test shows that AV was not significantly better than AA.

Another interesting aspect of this experiment is the comparison of performance by the same hand in response to stimuli of the same modality when this response is occurring simultaneously with the opposite hand responding in the one case to the same stimulus modality and in the other to a different stimulus modality. To designate these performances, the following symbolization will be used. Previously, for example, the symbol VV indicated that S was responding with the left hand to visual signals coming in the left eye, while the right hand was responding to independent visual stimuli coming in the right eye. The results in this case were taken from the Total clock which represented the dual hand function. To describe individual hand function, the upper case letter will indicate the hand being measured and the modality of the stimulus to which this hand is responding. The lower case letter will indicate the hand not being measured and the stimulus modality to which it is responding. As an example, the symbol Va indicates that the left hand response is being measured and the stimuli to which it is responding are visual and are coming in the left eye. Simultaneously the right hand is responding to independent signals coming in the right ear but this performance is not being measured in the analysis. The comparisons of interest are those which compare response to visual stimuli when the accompanying stimuli are visual and the response of the same hand under the same stimulus conditions when the accompanying stimuli are auditory. Also to be compared, will be the response to auditory stimuli when the accompanying stimuli are auditory and when they are visual.

A graphic display of these comparisons is shown in Figs. 10-13 for each S. It can be readily seen that visual performance when accompanied by visual performance is superior to visual performance when accompanied by auditory performance. Auditory performance, however, is superior when accompanied with visual rather than auditory performance. In order to verify these observations, Ss' performances for the appropriate hands were examined by the test of orthogonal comparisons. The scores were taken for each S at the same trial blocks used in the previous analysis. The results are shown in Table 3.

TABLE 3

SUMMARY TABLE COMPARING
INDIVIDUAL HAND PERFORMANCE

Source	df	Sums of Squares	Mean Squares	F	p
Between Subjects	3	.050	.016	2.67	NS
Within					
Conditions	3	.847	.282	47.00	$p < .01$
aV/Av	1	.009	.009	1.50	NS
vV/aV	1	.411	.411	68.50	$p < .01$
Av/Aa	1	.039	.039	6.50	$.01 > p < .05$
Error	9	.051	.006		

A point of clarification is entered here with respect to the symbols. Since performance in AV was counterbalanced over Ss with respect to hands used in the different stimulus modalities, 2 Ss performed AV and 2 performed VA. The individual hand performance is included for all 4 Ss in the computation of the above results and for simplicities sake, performance of auditory with visual has been designated Av. Consequently it appears that we are comparing auditory performance of the left hand only with visual performance of the right hand only. This is not the case, as each condition has measures representing the performance of 2 Ss using the

Fig. 10. Reciprocal of mean cumulative response time in .001-min. plotted as a function of 5-trial blocks for Subject 1. The parameters permit a comparison of response speed and acquisition within hands to the same stimulus class when the other hand is responding to the same and different stimulus classes.

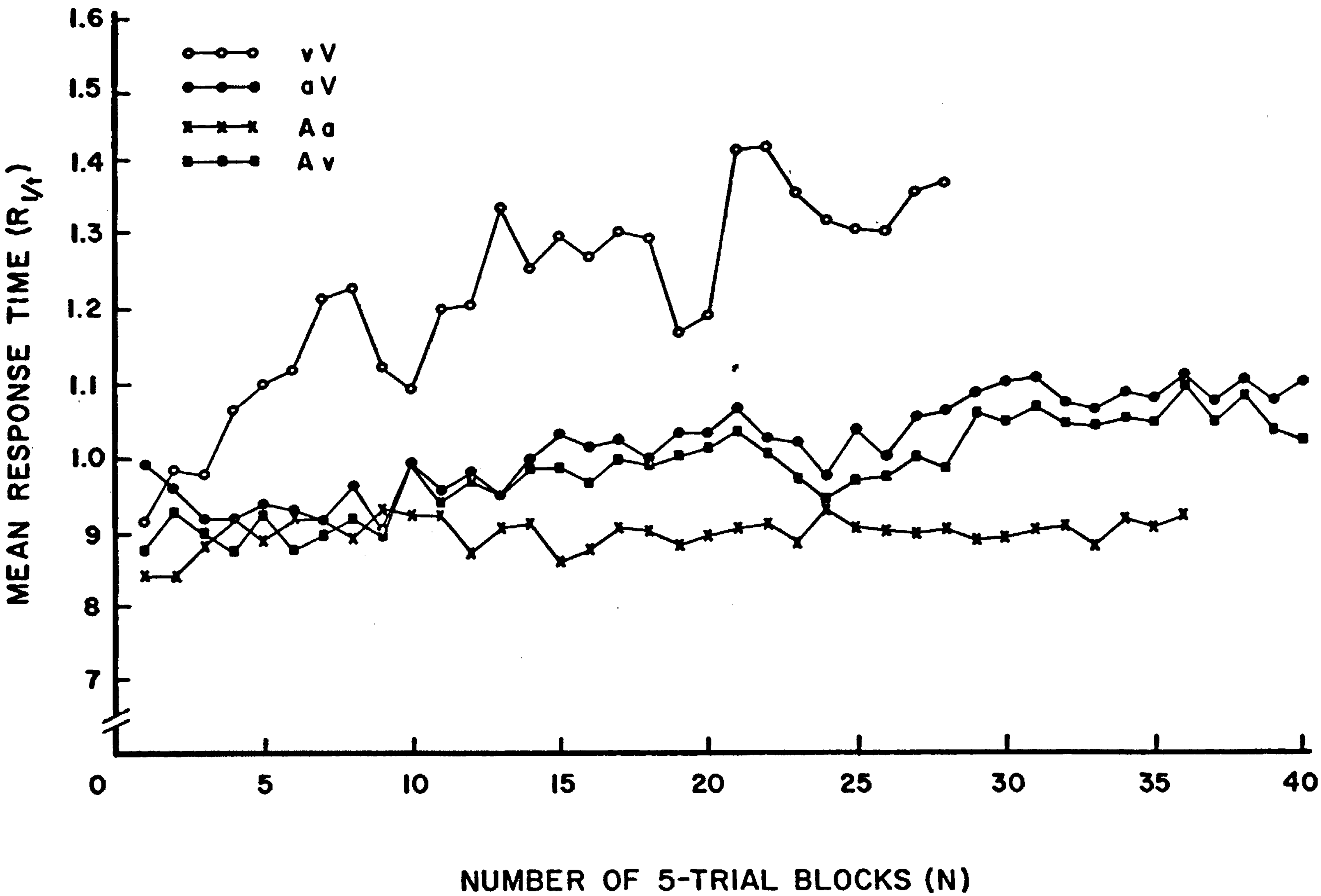
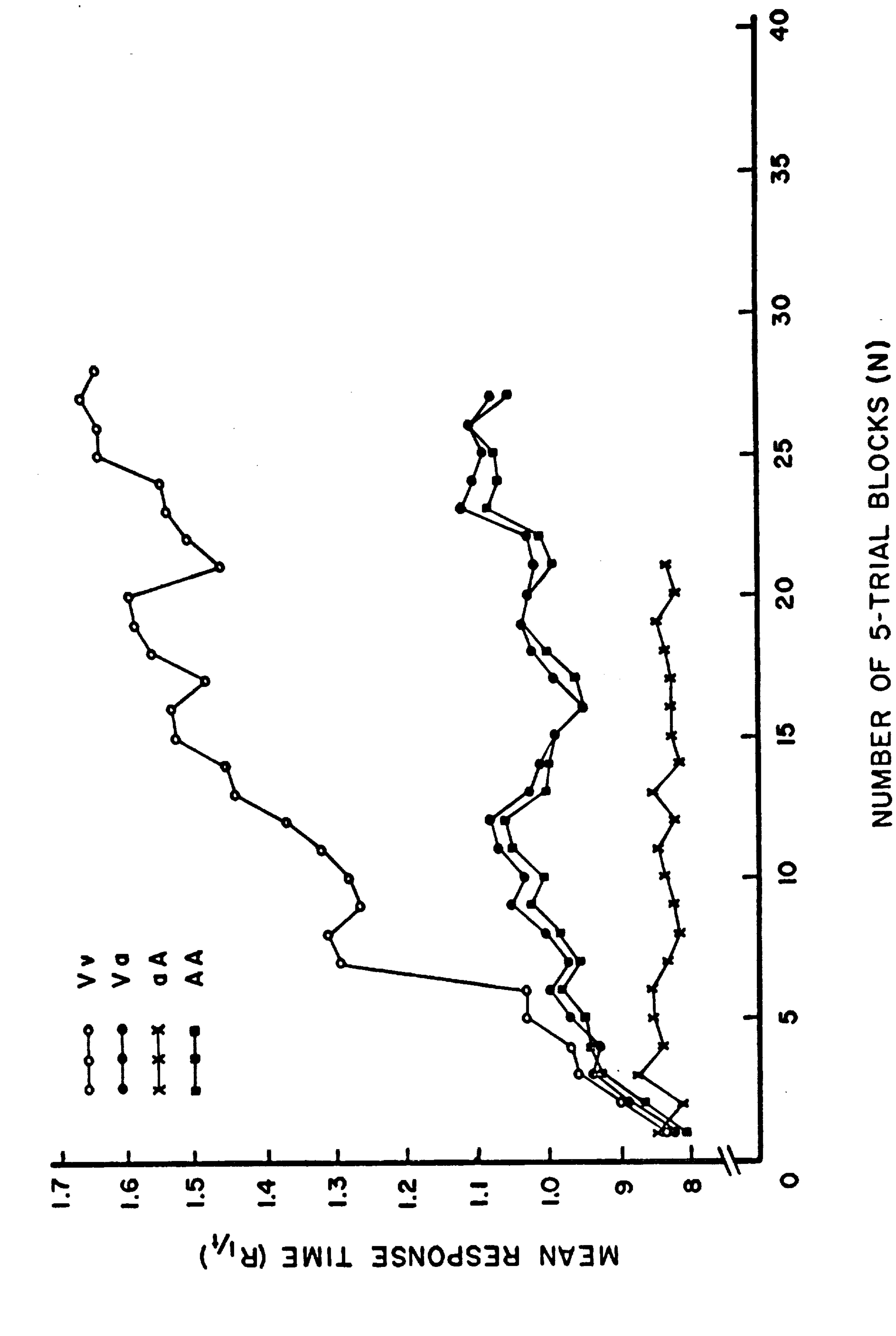

vV
aV
Aa
Av
MEAN RESPONSE TIME ($R_{1/t}$)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
9
8
7
0
5
10
15
20
25
30
35
40
NUMBER OF 5-TRIAL BLOCKS (N)

Fig. 11. Reciprocal of mean cumulative response time in .001-min. plotted as a function of 5-trial blocks for Subject 2. The parameters permit a comparison of response speed and acquisition within hands to the same stimulus class when the other hand is responding to the same and different stimulus classes.



MEAN RESPONSE TIME
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
9
8
Vv
Va
aA
AA
0
5
10
15
20
25
30
35
40
NUMBER OF 5-TRIAL BLOCKS (N)

Fig. 12. Reciprocal of mean cumulative response time in .001-min. plotted as a function of 5-trial blocks for Subject 3. The parameters permit a comparison of response speed and acquisition within hands to the same stimulus class when the other hand is responding to the same and different stimulus classes.

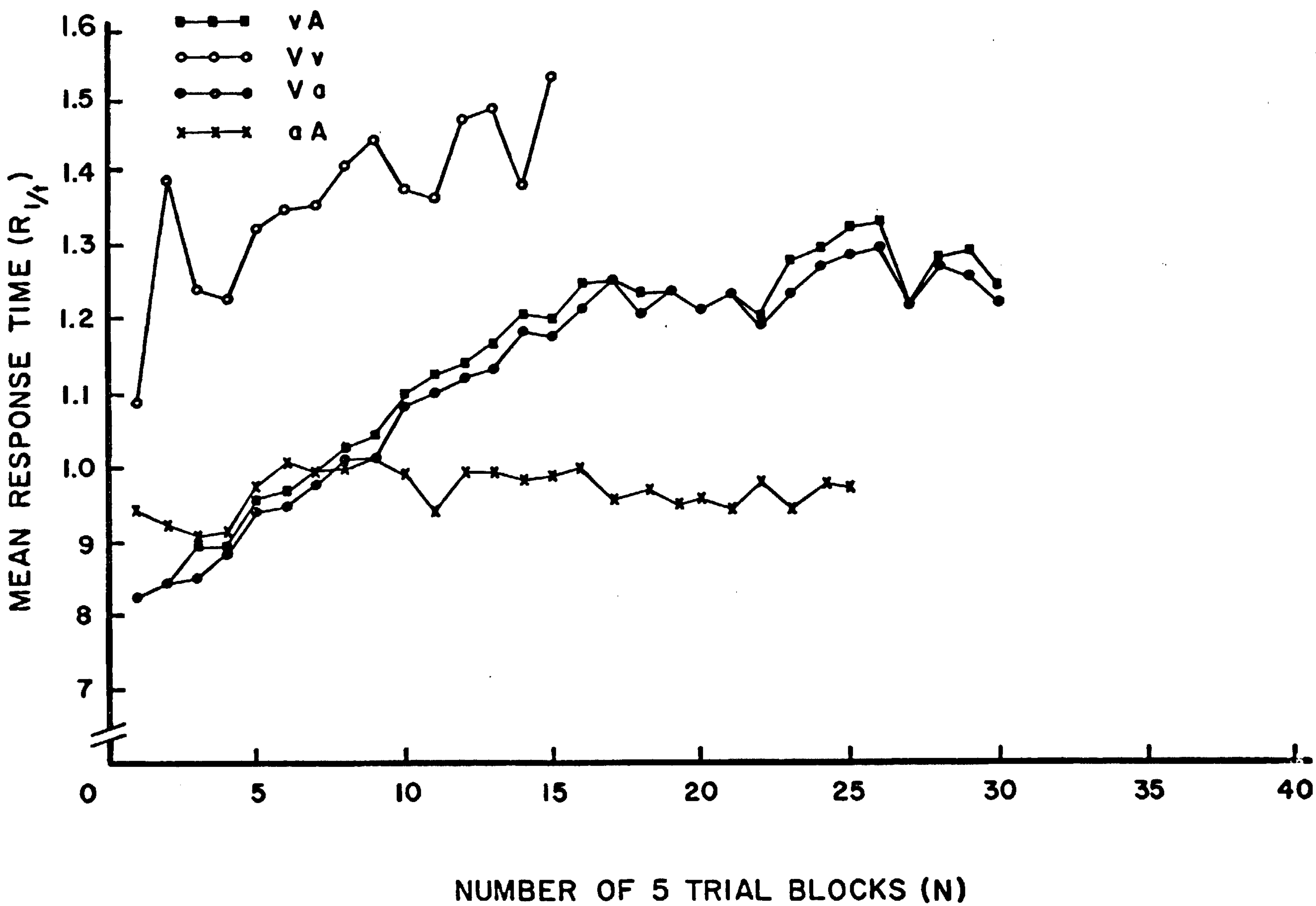
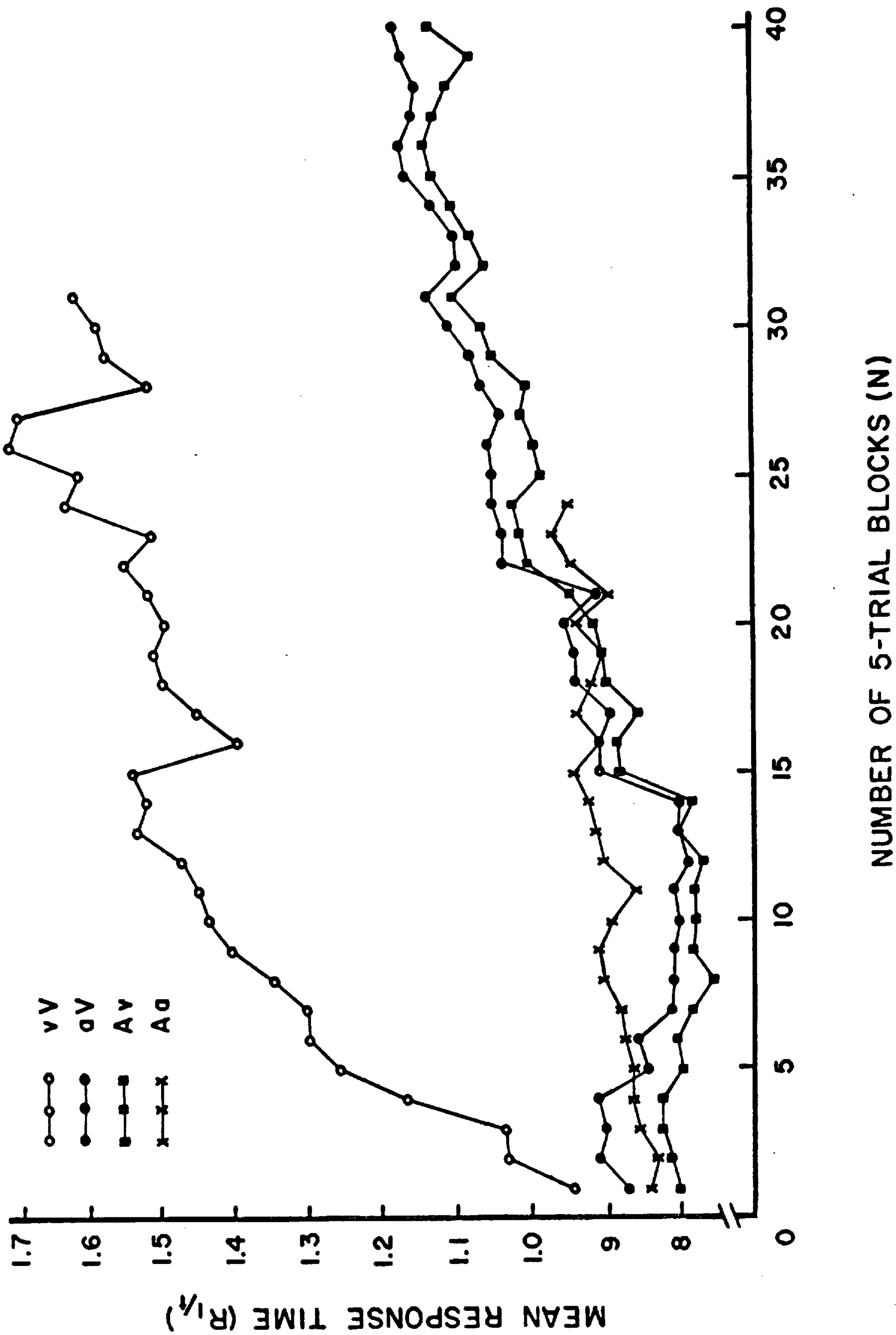

vA
Vv
Va
aA
MEAN RESPONSE TIME ($R_{1/t}$)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
9
8
7
0
5
10
15
20
25
30
35
40
NUMBER OF 5 TRIAL BLOCKS (N)

Fig. 13. Reciprocal of mean cumulative response time in .001-min. plotted as a function of 5-trial blocks for Subject 4. The parameters permit a comparison of response speed and acquisition within hands to the same stimulus class when the other hand is responding to the same and different stimulus classes.



vV
aV
Av
Aa
MEAN RESPONSE TIME ($R_{1/t}$)
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
0
5
10
15
20
25
30
35
40
NUMBER OF 5-TRIAL BLOCKS (N)

right hand and 2 S using the left hand in each condition. The legend on Figs. 10-13 will clarify this point. Handedness was not allowed to become a factor in this experiment. In addition an examination of scores was made with respect to the handedness of the Ss and there was no indication of facilitation.

The results shown in Table 3 support the observations made on the basis of the graphic displays. In addition it is noteworthy that there is no significant difference between visual and auditory performance when they are paired.

The significant differences resulting from the analysis immediately generated interest in their cause. A question of importance was whether the difference due to conditions resulted from S's ability to decode as a function of sense modality of input. Or was S perfectly capable of decoding and the difference was due to the length of time required for this process? To help clarify this question, a test of orthogonal comparisons of the number of correct responses for precisely the same conditions used in the previous test was conducted. The scores were taken from the same trial blocks as those used in the previous test. The results are shown in Table 4.

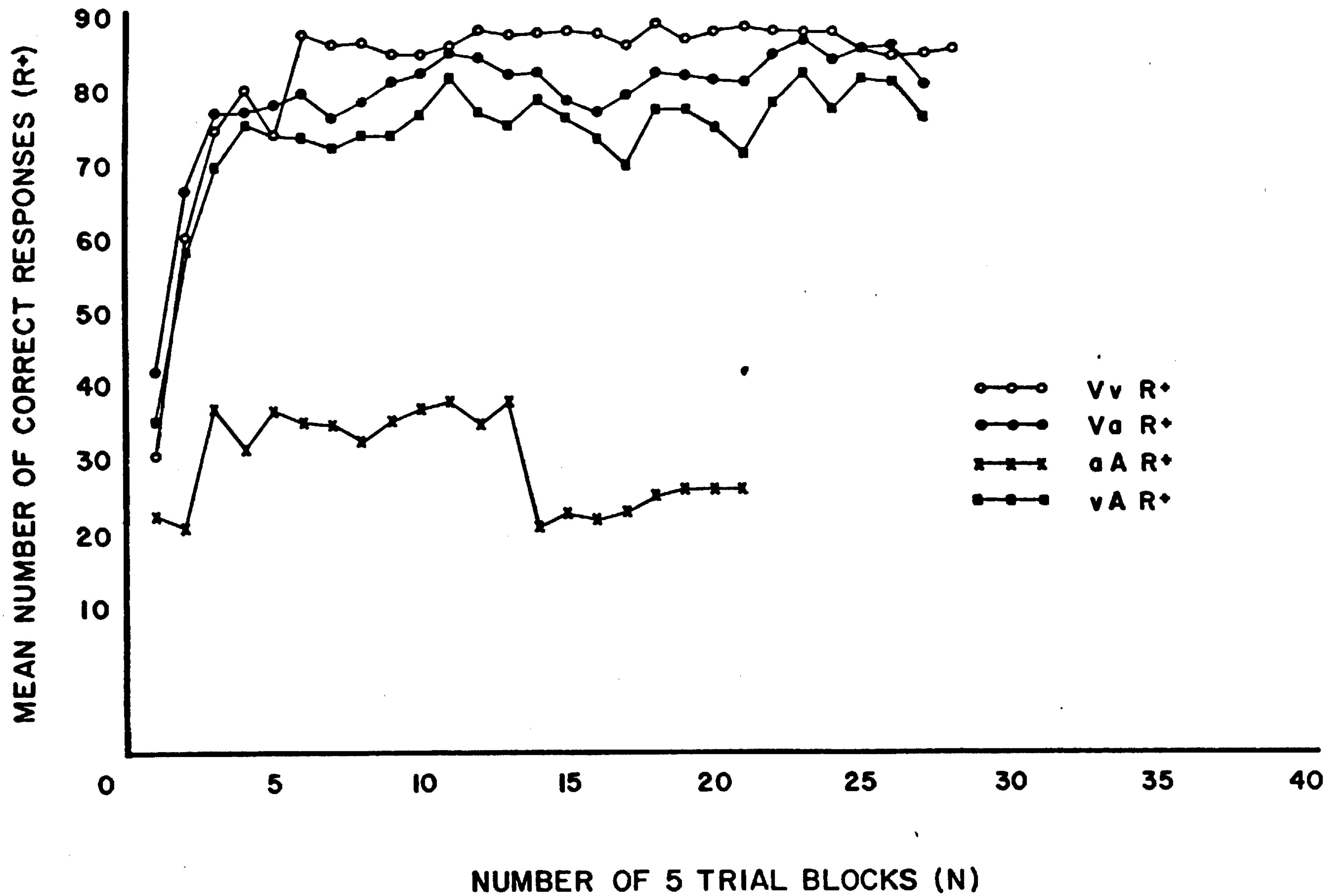
TABLE 4

SUMMARY TABLE COMPARING
NUMBER OF CORRECT RESPONSES

Source	df	Sums of Squares	Mean Square	F	p
Between Subjects	3	403	134.33	2.741	NS
Within					
Conditions	3	4609	1566.33	31.96	$p < .01$
vV/aV	1	144.50	144.50	2.95	NS
aV/Av	1	40.50	40.50	.826	NS
Av/Aa	1	2080.12	2080.12	42.45	$p < .01$
Error	9	441	49		

The table shows that there was no significant difference in number of correct responses between Ss. There was a significant difference in number of correct responses as a function of conditions. The difference between visual performance when paired with visual performance as compared to visual performance when paired with auditory performance cannot be due to the fact that the existance of the necessary auditory response interferes with S's ability to identify the stimulus. There was no significant difference in the number of correct responses in the vV and the aV condition. There is a significant difference between the number of correct responses to auditory stimuli when they are paired with visual and when they are paired with other auditory responses. It follows that paired with visual function, the organism can decode the auditory stimuli, even though both are independent of each other. The presence of two auditory stimuli inhibits the organisms' ability to decode even though the stimuli have unilateral organization. The major portion of the variance contributing to the significant difference resulting from conditions in Table 4 must be attributed to the inability to decode auditory signals when they are accompanied simultaneously by other auditory signals. A graphic demonstration of the relationship of correct responses to performance is shown in Fig. 14. This figure shows the number of correct responses for Subject 2 for the identical conditions shown in Fig. 11. It is readily seen that correct responses to aA are not in the same class as correct responses to the other conditions.

Fig. 14. Mean number of correct responses plotted as a function of 5-trial blocks, for Subject 2. The parameters represent the identical conditions found in Fig. 11 where time was plotted as a function of trial blocks.


MEAN NUMBER OF CORRECT RESPONSES (R+)
90
80
70
60
50
40
30
20
10
0
5
10
15
20
25
30
35
40
NUMBER OF 5 TRIAL BLOCKS (N)
Vv R+
Va R+
aA R+
vA R+

CHAPTER V

DISCUSSION

Physiological considerations. It has been noted that two dimensional sensory input functions, in the past, have been defined as multi-channel by the fact that two sensory input mechanisms have been presented independent signals. Condition VV was organized under this principle and by the use of the septum care was taken to assure that inputs into one eye were not available to the other. The central fixation point assured that the input to each eye would enter via the nasal field and as a result would be projected contralaterally, since the path from the nasal retina crosses at the optic chiasma. Physiological studies indicate that retinal images are projected isomorphically on the lowest level of the occipital cortex, Brodmann's Area 17. Beyond Area 17, the connections become extremely diffuse and excitation within Area 18 is dispersed in a wide pattern of activity over the entire area, both contralateral and ipsilateral (Osgood, 1953).

It is reasonable to believe then that the independent images maintain their uniqueness to Area 17. Because of the dispersion occurring in Areas 18 and 19, however, it is also reasonable to believe that the two images at this level become a unit of two components. Thus the net result is the same as would have occurred if the septum had not been present; the septum was insurance against the individual retinae receiving paired stimulation. The paired stimuli at the cortex are reduced to a pattern comparable to that created by two point sources of light. The pattern has a spatial configuration which is the code that determines the response. Two point sources of light are well within the limits of subitization, hence input characteristics should be in the same region as those of a single point source of light.

The conceptualization which produced Condition AA was based on the same considerations as that which produced condition VV. Independent stimuli were presented simultaneously to each ear. The auditory track provides contralateral projections at the ventral cochlear nucleus, the dorsal cochlear nucleus and the inferior colliculus, all of which occur prior to the projection on the cortical auditory centers. As a result, maintaining separation of simultaneous inputs in each ear is virtually impossible without invoking some attentional function which inhibits one input while attending to the other. Since the auditory system can code tones readily only in terms of pitch, loudness and time, from the listener's perceptual viewpoint, the spatial configuration which provides a code for the VV condition is not available to Condition AA. It can be argued that the pitch effect of the combined frequencies presented to each ear could ultimately be learned as a unit and responded to with the appropriate unitary response. The results indicate that, in the time parameters used in this study, this did not occur. The number of correct responses for each hand for each subject fell in the range of 30 to 40 correct responses per trial per hand out of a possible 90 for each hand. A reasonable deduction is that this degree of skill resulted from attentional shifts.

Thus, that which made VV possible and AA impossible can be attributed to the physiological characteristics of the organism. The difference existing between the remaining three conditions cannot be dealt with as simply.

Condition VV and Condition NN. One of the more interesting results of this study comes from a comparison of Condition VV and Condition NN. The question to be answered was, "In what way, if any, does information processing of two point source stimuli differ from information processing of a single source stimulus containing the same amount of information?" Information used in the question is based on experimenter-defined relative frequency probability measures.

The first item that becomes apparent in attempting to conceptualize this problem is that, in order for a single source to contain the same information as two sources, it is necessary to code one information source in terms of a higher order abstraction. Then one must combine it with a source having the same level of abstraction as it has in the simpler presentation. One can imagine several higher order abstractions which could provide an adequate code for this situation, such as color, shape, size, numbers, etc. In this study numbers were selected as the higher order abstraction because of the availability of Nixie tubes and the requirements of BURP. A septum could have been used in this condition without producing a different result, since those portions of the number image on each side of the septum would be reconstructed in areas 18 and 19 into a single unitary figure.

Since response times to NN were systematically slower than response time to VV while the information content for each condition was equal in terms of experimenter defined relative frequency measures, the decrement for NN must be attributed to the complexity of the higher order abstraction in the code. Thus simply defining information content of a stimulus in terms of relative frequency measures is not adequate. The information value of the event based on the event occurrence or the surprisal value of the event must be weighted by the information contained in the stimulus itself. 'Stimulus attributes' then, must be information coded also to arrive at a proper informational value of the stimulus event.

The meaning of Condition AV. In Condition AV we have an interesting situation because it is possible to compare the results of this study with those of the study by Adams and Chambers which investigated the same general paradigm.

In the Adams and Chambers study, S did not push buttons as a response. The task required S to move a stick either forward or back. The movement did not have to be graded as the throw of the stick was mechanically limited. The presentation of the stimuli differed in that the visual stimuli were viewed binocularly and the auditory stimuli were heard binaurally. The interstimulus interval in the Adams and Chambers study was 2-sec. as compared to 1-sec. in the present study and the number of uncertain stimuli in each sensory dimension was 2, allowing four possible combinations. In the present study, each sensory dimension had 3 alternative stimuli available to it, providing 9 possible combinations. Table 5 shows a comparison of the mean correct response times for each event for Av and aV in the Adams and Chambers study and the present study.

TABLE 5

COMPARISON OF MEAN CORRECT RESPONSE TIMES

Adams and Chambers		Chambers	
Auditory Av	Visual aV	Auditory Av	Visual aV
.364-sec.	.357-sec.	.592-sec.	.578-sec.

It is reasonable to believe that because of the nature of the response manipulanda used in the Adams and Chambers study, the difference shown in the table above is a little less than it might have been had the same manipulanda been used in both studies. It should also be noted that Ss in the Adams and Chambers study processed their information well within the .5-sec. period indicated as the PRP but Ss in the present study required somewhat more time than .5-sec.

Unless it is presumed that viewing a single stimulus with one eye is essentially different from viewing it with both eyes or that listening to a tone with one ear is essentially different from listening to it with both ears, the difference in the two studies was in the realm of the amount of information transmitted. The present study contained more information in the stimulus and this difference can be quantified. Each stimulus in each sensory dimension in the present study contained 1.58-bits while each stimulus in each dimension in the Adams and Chambers study contained only 1-bit. Each stimulus pair in the present study contained 3.17-bits as compared to 2-bits in the previous study.

The difference in interstimulus interval between the two studies is also pertinent to the amount of information transmitted. Although the time domain has not been scaled in information terms, it is generally conceded that within limits a reduction of time between sequential stimuli appears to increase the difficulty of decoding the stimulus. Hence, the 1-sec. inter-stimulus interval in the present study as compared to the 2-sec. inter-stimulus interval of the Adams and Chambers study, probably contributed to the increase in response time. How much was contributed by this factor will not be determinable until a method has been found to scale time in information terms.

The study and the information hypothesis. It was postulated previously that a systematic relationship existed between information and response time. In other words, rate or capacity for information processing is systematically related to the amount of information requiring processing. In support of this position, the mean of the correct response times for the right and left hands is shown as a function of conditions in Table 6.

TABLE 6

MEAN CORRECT RESPONSE TIMES FOR RIGHT AND LEFT HAND

	Left	Right
AV	.59-sec.	.58-sec.
VV	.44-sec.	.43-sec.
NN	.55-sec.	.53-sec.

It has been argued that Condition NN contained more information in the stimulus than did Condition VV. The greater speed in responding to VV is in accordance with the hypothesis. The difference between NN and AV is more difficult to explain. The results suggest that precision of discrimination functions vary with the sensory modality used. If this is the case it is reasonable to conclude that increasing the number of alternative stimuli from 2, as used in the Adams and Chambers study, to 3, as used in the present study, resulted in a greater increase in information content for the auditory stimuli than for the visual stimuli. This assumption leads to the conclusion that the equation relating information to response time must include a parameter value which represents the sense modality being used to transmit the information.

The results of the comparisons vV-aV and Aa-Av are in conformity with similar comparisons made in the Adams and Chambers study. The constraint of time simultaneity between stimulus pairs is necessary to their being processed in the time allowed. An item of interest here is that in the earlier study auditory responses were slowed down to the speed of the visual responses, the latter being in the same speed range as responses made to visual stimuli when not accompanied by auditory stimuli. In the present study responses to visual stimuli in the presence of auditory stimuli were slowed when compared to responses to visual stimuli in the presence of visual stimuli. Responses to auditory stimuli on the other hand, increased in speed when paired with visual stimuli as compared to the speed of response to auditory stimuli when paired with auditory stimuli. The only conclusion that can be drawn here is that simultaneity is maintained throughout the communication channel and the mean time for both responses is dependent on the response of the slower component. The dependency on simultaneity indicates that both within and across the sensory modalities tested, the human organism is a single channel processing system. It should be noted, however, that at the level of information transmitted in this study, simultaneity is a necessary but <u>not</u> a sufficient condition to produce information processing in the time range sampled, as indicated by the results of <u>AA</u>.

<u>Conclusion</u>. The results of this study suggest that to establish a relationship between information and response time, the following measures are necessary:

1. A measure which reflects the probability of the occurrence of a unit event.
2. A measure which reflects the information contained in the stimulus as a function of the 'stimulus attributes'.
3. A measure which reflects the information value of the time parameters.
4. A measure which reflects the peculiar characteristics of the sense modality over which the information is being transmitted.
5. A measure of the information carried in the response. (This item was not investigated in the

study since response information was maintained as a constant for all stimulus conditions but is indicated in the comparison of the Adams and Chambers study and the present study.)

Equation 3, the Shannon-Wiener measure of information, includes Item-1 only. A new equation must be developed which will attempt to account for all the parameters indicated above.

If we postulate that the information contained in the 'stimulus attributes' is represented by a factor W which we further write as a function of a probability Q,

$$W_a = Q_a \operatorname{Log}_2 1/Q_a \qquad [4]$$

and the same function for time is,

$$W_t = Q_t \operatorname{Log}_2 1/Q_t \qquad [5]$$

We can also postulate that the information carried in the response is represented by

$$W_r = Q_r \operatorname{Log}_2 1/Q_r \qquad [6]$$

and the parameter value associated with the sense modality is represented by the symbol β.

We can then combine these measures to get 'surprisal' of a particular alternative,

$$h_i = \beta\left[(\operatorname{Log}_2 1/Q_a \operatorname{Log}_2 1/P_a) + (\operatorname{Log}_2 1/Q_t \operatorname{Log}_2 1/P_t) + (\operatorname{Log}_2 1/Q_r \operatorname{Log}_2 1/P_r)\right] \qquad [7]$$

and the information of the source is,

$$H = \beta \left[\sum_{a=1}^{N_a} (P_a\ Q_a\ \mathrm{Log}_2\ 1/Q_a\ \mathrm{Log}_2\ 1/P_a) + \sum_{r=1}^{N_r} (P_r\ Q_r\ \mathrm{Log}_2\ 1/Q_r\ \mathrm{Log}_2\ 1/P_r) + \sum_{t=1}^{N_t} (P_t\ Q_t\ \mathrm{Log}_2\ 1/Q_t\ \mathrm{Log}_2\ 1/P_t) \right] \qquad [8]$$

Whether the information equation described in [8] is a useful description of the information, is dependent on the adequacy of the scales used to define the parameters of stimulus attributes, time, and response. Since these scales have yet to be developed, judgment of the adequacy of the information hypothesis must wait upon experimental investigation for determination.

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